CLASSIFICATION OF FAULTS IN POWER TRANSFORMER USING FUZZY LOGIC AND WAVELET TRANSFORMS

A Thesis Submitted in Partial Fulfilment of the Requirements for the Award of the Degree of Master of Technology

in

Electrical Engineering

(Industrial Electronics)

By:

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NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

PIN-769008, ODISHA

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To

My parents

CERTIFICATE

This is to certify that the dissertation entitled **"CLASSIFICATION OF FAULTS IN POWER TRANSFORMER USING FUZZY LOGIC AND WAVELET TRANSFORMS"** being submitted by **Shubham Sharma**, **Roll No. 212ee5267**, in partial fulfillment of the requirements for the award of degree of **Master Of Technology In Electrical Engineering (INDUSTRIAL ELECTRONICS)** to the **National Institute of Technology**, **Rourkela**, is a bonafide record of work carried out by him under my guidance and supervision.

(**Dr. Gopalakrishna Srungavarapu)**
Assistant Professor
Department of Electrical Engineering
NIT Rourkela

Date:

Place:

DECLARATION

I hereby declare that the investigation carried out in the thesis has been carried out by me. The work is original and has not been submitted earlier as a whole or in part for a degree/diploma at this or any other institution / University.

Shubham Sharma

ACKNOWLEDGEMENT

I am mainly indebted to my guide Dr. S. Gopalakrishna who acts like a pole star for me during my voyage in the research by his infusion, support, encouragement and care. I express my deep regard to him for the successful completion of this work. . His ideas and suggestions were helpful for timely accomplishment of the target aimed. His heart being a great ocean of compassion and love not only created friendly environment during my work with him but also enlightened my soul.

I am thankful to Prof. Anup Kumar Panda, Head of the Department of Electrical Engineering, National Institute of Technology, Rourkela, for providing me facilities to carry out my thesis work in the Department of Electrical Engineering.

I express my sincere gratitude to all the faculty members of Department of Electrical Engineering, NIT Rourkela for their affection and support.

I am thankful to all the staff members of Department of Electrical Engineering, National Institute of Technology, Rourkela for their support.

I render my respect to all my family members and my well-wishers for giving me mental support and inspiration for carrying out my research work.

I thank all my friends who have extended their cooperation and suggestions at various steps in completion of this thesis.

Shubham Sharma

ABSTRACT

With the day to day increase of the power and the increasing rate of industrialization. The amount of power to be developed and the safety of the power transformers have increased manifolds. For optimum results it is required to have nearly a no – fault operation of power transformer. The objective of this thesis is to design a controller or method which could predict the unwanted outages in a small interval of time and with accuracy. The controllers like PI, PID are in use in industries over a decade and found to be very useful also. But in this case these controllers are not found to give reliable results due to the oscillating and non – periodic nature of the power transients. Hence, fuzzy controller being an intelligent controller could be used for this purpose of detection of inrush and fault current.

The wavelet transform with its ability to determine information from transient signals both in frequency and time domain is also used for detailed analysis of various power transformer transients. Further it is found that wavelet transform is a very effective tool for detailed analysis of these transients and also with fuzzy logic we have obtained accurate and very useful results.

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ABBREVIATIONS

FFT	Fast Fourier Transform
DWT	Discrete Wavelet Transform
CT	Current Transformer
KV	Kilovolt
PID	Proportional Integral and Derivative
CRGO	Cold rolled grain oriented

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

In today's world of technology and comfort, the need for power and its protection has increased many folds. The demand for a reliable supply of electrical energy for the exigency of the modern world in each and every field has increased considerably requiring nearly a no-fault operation of power systems. A number of industries have been set up in our country as a result the need of continuous supply has also increased. The Power Transformers are bulky and expensive devices which need to be protected from different fault conditions. The crucial objective to mitigate the frequency and duration of unwanted outages related to power transformer puts a high pointed demand on the power transformer protective relays to operate immaculately and capriciously.

The protection of power transformer has become a challenging job due to the somewhat similar phenomenon observed during inrush and internal fault occurrence. Also the type of faults and its locations varies a lot as single – phase to ground fault, two phase to ground fault, three phase to ground fault, inter turn fault, external line to line fault etc. There are problems which are peculiar to transformer, which are not encountered in other items of power system. One of the major problems is the large magnetizing inrush current, whose magnitude can be as high as internal fault current and may cause false tripping of the breaker. A common differential relay operating on the basis of measurement and evaluation of currents at both sides of the transformer can't avoid the trip signal during inrush condition.

As inrush is a necessary phenomenon which will occur while the switching of transformer takes place. So, the circuit breaker should not trip at the time of occurrence of inrush while fault current having the same high magnitude harmonics, at that time the circuit breaker should trip to protect the power transformers from damage.

1.2 MOTIVATION

Harmonic – restrained differential relay is based on the fact that the magnetizing inrush current has a large second harmonic component, and nowadays the above technique is widely applied. But this technique must be modified because harmonics occur in normal state of power system and the quality of second frequency component in inrush state has been decreased because of improvement in core steel. There are cases in which the presence of differential currents cannot make a clear distinction between fault and inrush. New relaying technique with high reliability is required for flexibility in spite of change of condition in power system.

Recently, to advance the conventional approaches, several new AI (artificial – intelligence) features for protective relaying have been developed. Fuzzy logic is one of the artificial intelligence method which is a very effective tool applied in a number of fields. It is a intelligent logic with a predictive way of approach.

1.3 THESIS OBJECTIVE

- The objective of my thesis is the study of power transformers different phenomenon's:

I. Inrush Current at different switching angles

II. Internal Fault Analysis
   a) Single line To ground fault
   b) Double line to ground fault
   c) Three line to ground fault

III. External Fault Analysis
   a) Single line to ground fault
   b) Double line to ground fault
   c) Three line to ground fault

- Detail analysis of the three cases using some of the transform method such as Wavelet transform, Discrete Fourier transform etc.

- Developing a fuzzy logic control method to differentiate the three cases using one of the transform methods.

1.4 LITERATURE SURVEY

In the literature of power transformer protection, the key issue lies in discriminating between transformer transients (magnetizing inrush current and internal fault current). It is natural that relay should be initiated in response to internal fault but not to inrush current or over-excitation/external fault current [6].

A method based on Clarke's transform and fuzzy logic to operate the differential relay in a way so as to differentiate the inrush and internal fault and trip the relay for internal fault [2]. Studied the operation of a differential relay and percentage differential relay, also studied the different behaviour of differential relay during normal operation, inrush condition, internal fault current operation, external fault current operation and spill current for the same [4].

The analysis of inrush and fault currents and then applied the wavelet transform to depict the varying behaviour and operating the relay during occurrence of fault using neural network [1]. This paper presented a base for the operation of relay during inrush and internal fault. Also presented that the harmonics during the inrush and fault current are quite similar which we need to differentiate using some transform method such as wavelet transform, Clarke's transform etc.

A digital protective relaying algorithm for power transformer using fuzzy logic was developed [3]. This paper presented a method to differentiate the fault and inrush using flux – differential current derivative curve and percentage differential characteristic curve for the purpose of overcoming limits of conventional relaying. Conceptual Wavelets in Digital Signal Processing by D. Lee Fugal [4]. This is a text book on the basic concepts of wavelets and how to implement wavelets in practical approaches. This book also provided idea about the DWT implementation. A wavelet fuzzy expert technique for classification of Power transformer transients [5]. This paper presented a method of fuzzy logic implementation using wavelet transform. Also the rule base used in this paper is very useful in understanding the power transformer transients. The schematic diagram and the behaviour of the different fault cases and also the detailed study of the inrush and other transients was done [7, 10]. From paper [11] – [13] we have done detailed analysis of the different types of the core available. In paper [6] – [8] presents detailed study of how to use fuzzy logic with wavelet transforms for transformer protection.

1.5 THESIS LAYOUT

Chapter – 1: gives a brief idea about why to protect power transformer, different types of faults involved with it, and the previous methods which are used for power transformer protection.

Chapter – 2: deals with the inrush phenomenon in power transformer, different types of cores available and also their comparison, history of power transformer.

Chapter – 3: discusses about the fuzzy logic, its importance over other conventional logics, and foundation of fuzzy logic. In accordance with this, it also gives idea about DWT, importance of discrete wavelet transform and its comparison with other transforms.

Chapter – 4: covers the FFT analysis of the inrush, single line to ground internal and external faults, double line to ground internal and external fault and three line to ground internal and external faults. It also gives a conclusion of all this analysis.

Chapter – 5: covers the DWT transform analysis of the inrush and internal fault current.

Chapter – 6: deals with the fuzzy logic implementation in power transformer. It also gives us idea about the rule base framing and differentiation of various fault conditions.

Chapter – 7: gives the conclusion and the future scope of the project.

Chapter 2

INRUSH PHENOMENON IN POWER TRANSFORMER

2.1 POWER TRANSFORMER

Before invention of transformers, in initial days of electrical industry, power was distributed as direct current at low voltage. In the past, some 50 – 60 years back the electrical circuits were designed with same voltage and also the circuits of distribution system are small. So, only urban areas can get benefit of this and there was no supply in rural areas.

In 1885, the first transformer was developed and that changed the distribution and transmission system to great extent. Now with the development of transformers we can step up the low voltage level of the generated power to high voltage levels, so as to transmit it to longer distances. Also, if the power is transmitted at a higher voltage and lower current the transmission losses can be reduced to great extent. Use of transformers made it possible to transmit the power economically hundreds of kilometres away from generating station. After receiving the power at the receiving station with the use of step – down transformers we can reduce the voltage level to the desired level and also at different levels.

Power Transformers are the bulky and costlier devices installed at the generating side. The power is generated usually at a voltage in the range of (11 to 25 KV) is stepped up by a power transformer to a higher voltage (200, 345, 400 0r 765 KV) for transmission. The power transformer is a very expensive, bulky and critical component of the power systems. If one power transformer is being damaged it not only affects the transmission process but also the severe loss of money is involved. Power transformers usually have same or uniform load as at the distribution side the number of users are quite large in number. So, if one or two users are not operating at some point of time than also power transformer operates at full load condition.

2.2 INRUSH PHENOMENON

Inrush current is defined as the maximum, instantaneous input current drawn by an electrical device during starting or turn on. During energization of power transformer a transient current up to 2 to 5 times flow for several cycles and is known as magnetic inrush. This is due to saturation of magnetic core which in turn due to an sudden change in the system voltage which may be caused by switching transients and out-of-phase synchronization of a generator or restoration after the clearance of fault. It decreases slowly due to the damping effect of winding resistance and takes several cycles to settle to normal current value. The value of inrush current depends on the core material, residual flux and instant of energization. Other than energization inrush current in power transformer also occurs during voltage recovery after the clearance of an external fault or after the energization of a transformer in parallel with a transformer that is already connected to power system. Inrush current also consists of harmonics such as even and odd harmonics as well as it consists of dc offset. The second harmonic content during the starting is less and its magnitude increases with the progress of time and with the decrease in inrush current. The main problem associated with magnetizing inrush current is false operation of differential relay based on second harmonic restrain method in addition to damage of power transformer windings by increasing the mechanical forces like short circuit current if remain in a high value for longer time.

The inrush current is measured with the secondary being open and it is the high current harmonics which are present in the primary side of the transformer.
The inrush current in our block diagram could also be termed as the breaker current.

2.3 MATHEMATICAL DERIVATION OF INRUSH CURRENT

A power transformer is considered whose core is initially unmagnetized. The transformer primary winding is connected to a supply voltage v (t) and the secondary is made open.

The supply voltage is given by

$$v(t) = V_m \sin(\omega t + \theta) \tag{2.1}$$

the applied voltage is expressed as a function of flux in the core and primary current.

The applied voltage is given by

$$v(t) = Ri(t) + N\frac{d\phi(t)}{dt} \tag{2.2}$$

By neglecting the core loss and resistance equation (2.2) now becomes

$$v(t) = N\frac{d\phi(t)}{dt} \tag{2.3}$$

$$\Rightarrow \phi(t) = \frac{1}{N}\int_{-\infty}^{t} v(t)\,dt \tag{2.4}$$

$$\Rightarrow \phi(t) = \phi_{residual} - \phi_m[\cos(\omega t + \theta) - \cos(\theta)] \tag{2.5}$$

$$\phi_m = \frac{V_m}{N\omega} = \frac{\sqrt{2}\,V}{N\omega} \tag{2.6}$$

$$\Rightarrow \phi(t) = -\phi_m[\cos(\omega t + \theta)] + C \tag{2.7}$$

The second term in the equation (2.7) is the integration constant and its value depends on the residual flux in the transformer core and the phase angle of the applied voltage at the instant of switching during energization.

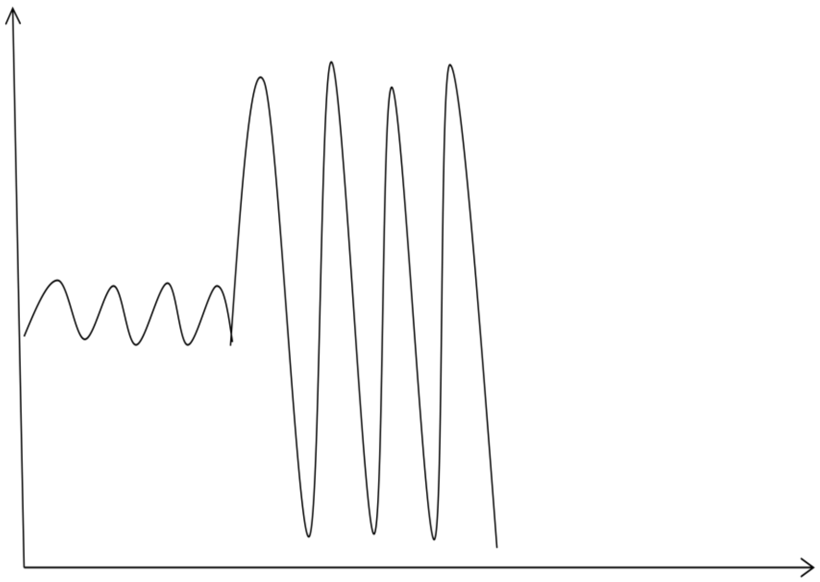
If the transformer is energized when the voltage is at its peak then the flux is given by equation (2.8).

$$\Rightarrow \phi(t) = -\phi_m[\cos(\omega t)] \tag{2.8}$$

Transformer residual flux is neglected i.e. $\phi_{residual} = 0$

Hence it is clear from the above equation that the constant C is zero. There is no transient in flux and the time variation of flux is

$$\phi(t) = \phi_m sin\left(\omega t - \frac{\pi}{2}\right) \qquad \text{(For } \omega t > \frac{\pi}{2}\text{)} \tag{2.9}$$



Time (s)

Fig 2.1: Inrush current when switching angle is 90 degree

If the transformer is energized when the voltage is zero then the flux is given by equation (2.9).

$$\Rightarrow \phi(t) = -\phi_m[\cos(\omega t)] + \phi_m \tag{2.9}$$

Transformer residual flux is neglected i.e. $\phi_{residual} = 0$

It is clear from the equation (2.9) that the constant C is equal to ϕ_m.

This equation shows that the flux can reach up to $2\phi_m$ at $\omega t = \pi$ which is double the peak value of the steady state flux in the transformer core under normal operating conditions. The inrush current is given in Fig 2.3 for the transformer that is energized when the voltage is at zero. It is clear that the inrush current in this case is much higher in comparison to the inrush current obtained during energization at voltage angle 90^0.

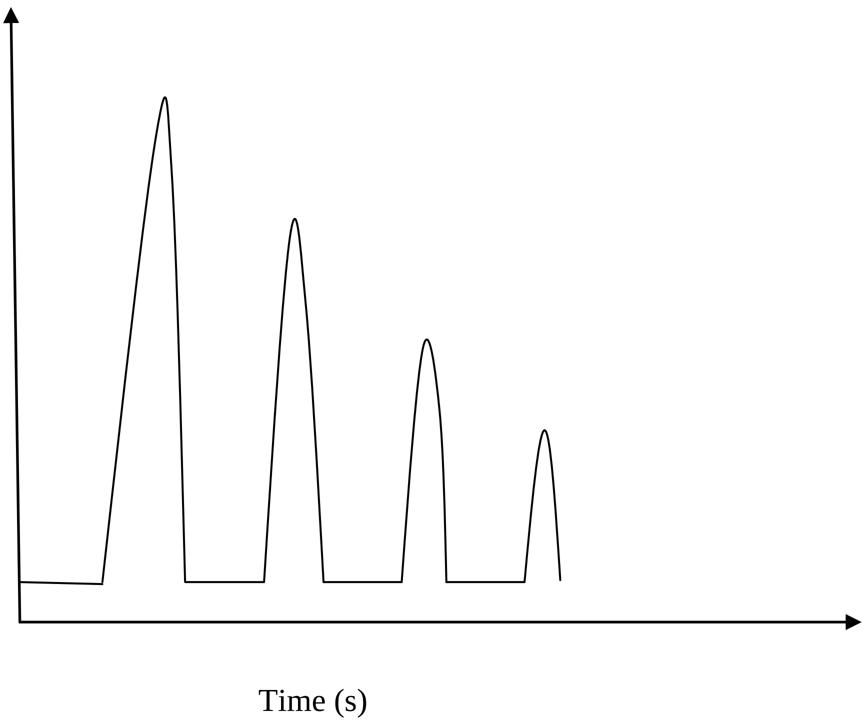


Fig 2.2: Inrush current when switching angle is 0 degree.

2.4 BLOCK DIAGRAM FOR INRUSH PHENOMENON

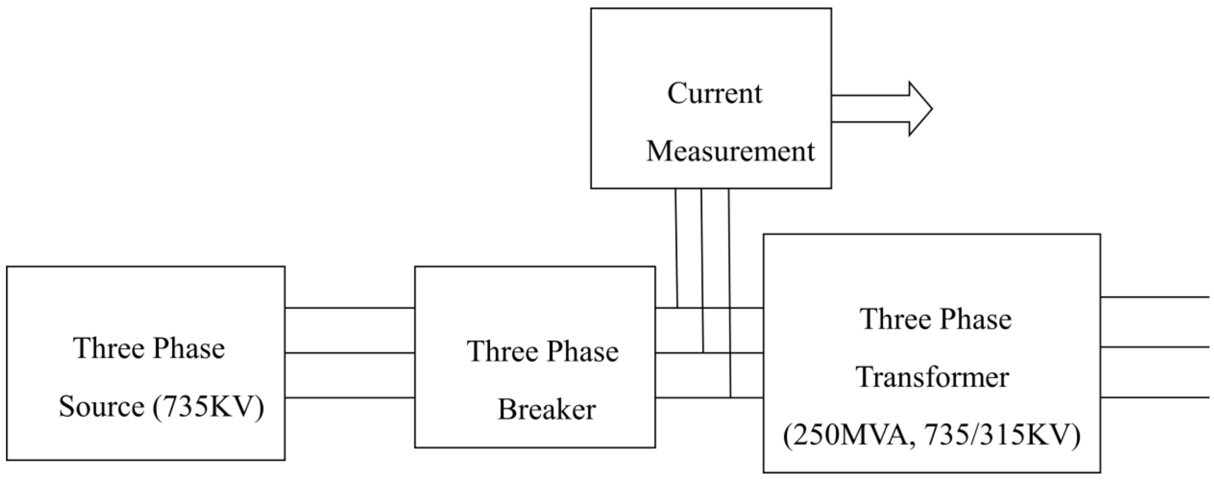


Fig 2.3: Block diagram for inrush phenomenon

2.5 COMPARISON OF AMORPHOUS CORE AND SILICON STEEL

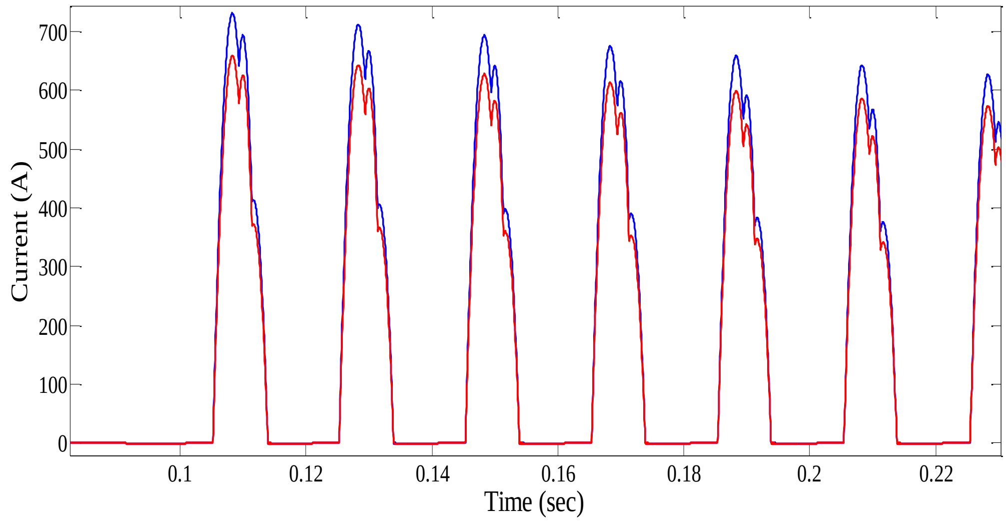
The core of transformer was at first made in around 1885. The core of first practical transformer was made up of carbon steel. But the losses in that was a lot. So, with the rapidly changing technology carbon steel was substituted by silicon steel and today most of the power transformers and distribution transformers uses cold rolled grain oriented silicon steel (CRGO) cores. These type of transformers consists of Si: 11Fe and it is available in around 5%. It is processed in such a way that the optimum properties are developed in the rolling direction, due to a tight control of the crystal orientation relative to the sheet. Due to the special method used in rolling these sheets the magnetic flux density increases by 30% compared to the previous sheets but magnetic saturation decreases by 5%.

CRGO is usually supplied by the producing mills in the coil form and it has to be cut into laminations which are then used to form a transformer core. But the asking demand of the world for low core losses, low magnetostriction lead to the development of amorphous alloy cores.

On the other hand Amorphous alloy exhibits easy magnetization and demagnetisation. It is due to the fact that in amorphous alloy's structure there is a random pattern in its metallic molecules as compared to the rigid structure of CRGO steel. The amorphous alloy is being made with exceptional quality automatic plants. These are thin ribbon type of cores with thickness of about 0.025mm. The received ribbons are extremely thin and then are cut down to the desired length and shape thus increases the magnetisation level. These thin strips are used in core building of different types.

Advantages of amorphous core are low core losses, low magnetising current, less zero sequence current, les noise, higher efficiency and longer life. However disadvantages are higher inrush current, more harmonic problem, bigger size and higher initial cost. There are several amorphous alloys in the market among which iron-boron-silicon alloy (Fe_{78} B_{13} Si_9) has presented best performance, the core loss is about (1/10) of core loss in CRGO steel. The saturation limit of amorphous alloy is 1.69 Tesla; however it is 2.03 Tesla for CRGO steel. Therefore, amorphous alloy shows good result when they are used in small size of transformers because of their low flux densities..

When a transformer is switched ON, the core is driven into saturation; therefore current inrush comes in picture. Because of low saturation limit of amorphous, the magnitude of inrush current is higher in case of amorphous core transformer compared to conventional CRGO core transformers. The inrush current in the inadvertent operation of overload relays.



Blue – Amorphous core

Red – CRGO steel

Fig 2.4: Inrush Current for Amorphous and CRGO steel

2.6 REMARKS

Transformer switching phenomenon being random makes the magnetizing inrush also random. During energization large magnitudes of currents flow into the primary winding of the transformer while no current flow out of the secondary. This is similar to condition during internal fault. So, we need to distinguish the two. Also we see that the inrush current for the amorphous core is greater than the CRGO steel, this is due to the fact that the magnetic flux density for CRGO steel is greater than that of the amorphous core.

CHAPTER 3

FUZZY LOGIC AND WAVELET TRANSFORMS

3.1 INTRODUCTION

Fuzzy logic is a logic which deals with uncertainty by modelling the events.
It deals with three entities:

i. Degree of accuracy /precision
ii. Uncertainty
iii. Vagueness (approximately equal)

In a narrow sense, fuzzy logic is a logical system, which is an extension of multi - valued logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In fuzzy logic, the truth of any statement becomes a matter of degree. Any statement can be fuzzy. The major advantage that fuzzy reasoning offers is the ability to reply to a yes-no question with a not-quite-yes-or-no answer. Humans do this kind of thing all the time (think how rarely you get a straight answer to a seemingly simple question), but it is a rather new trick for computers.

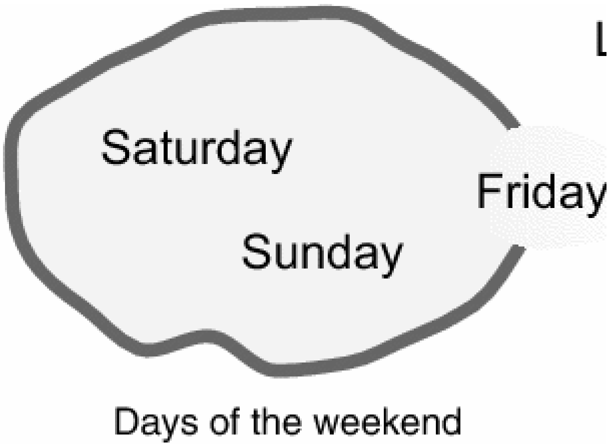
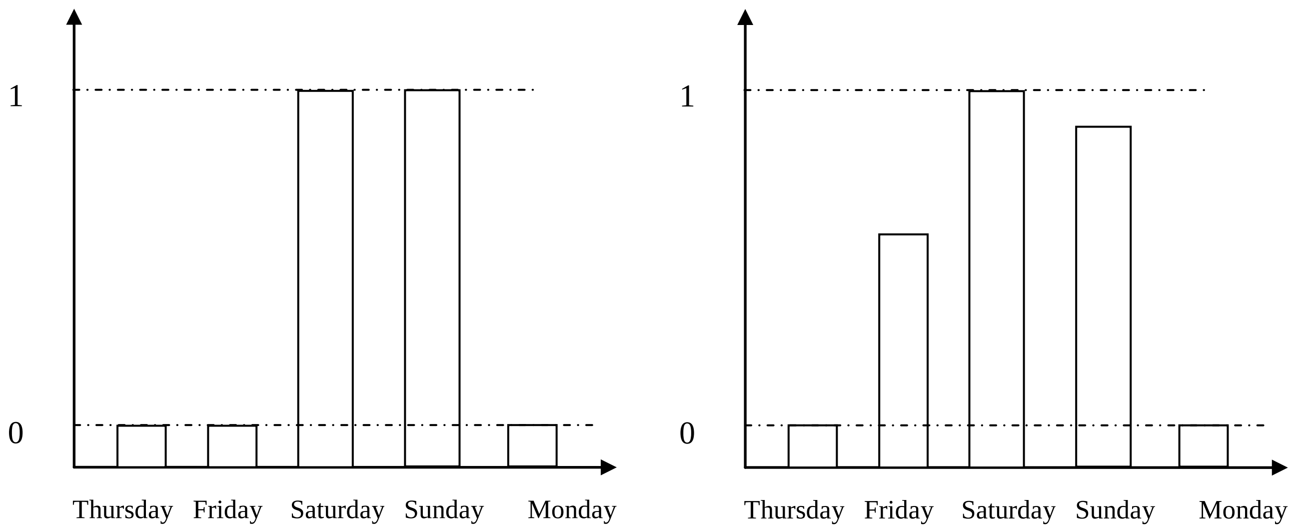


Figure 3.1 Representation of days of the weekend using fuzzy set

- **Let us take an example for defining the weekend using fuzzy logic:**

There are three days which comes in our mind when we talk about weekends. So, if we define these using two valued function we can either give 1 0r 0 to every day. But if we use fuzzy logic we can give different membership value to each day. Almost all will say that Saturday and Sunday are weekend. But if we see more precisely Friday is also somewhat weekend. This can be understood through the below graphs in Fig 3.2.

So, using fuzzy we need not to give exact responses or absolute answers. We can somewhat skip from the question or in a broader way can give somewhat varying answer.



Days of a weekend with two – valued membership Days of a week end with multi valued membership

Figure 3.2: Bar graph of classical set and fuzzy set

3.2 FOUNDATION OF FUZZY LOGIC

Fuzzy logic starts with the concept of a fuzzy set. We have a set defined as binary set because it can assign only binary values, means either 1 (full membership) or 0 (no membership). It cannot have values in between 0 and 1. On the other hand a fuzzy set is a set without a crisp, clearly defined boundary. So by using fuzzy logic we can assign values in between 0 and 1 or we can say that we can give answer of a yes/no question in partial yes/no. It gives the users a wide range of variation or choices.

3.3 MEMBERSHIP FUNCTION

A membership function is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1. With the help of membership function we can assign values in between 0 and 1 to a set, which gives us a degree of unprecisioness. There are different types of membership functions which we can use such as

i. Triangular
ii. Trapezoidal
iii. Gaussian or Singleton
iv. Sigmoid
v. Piecewise linear

- Why we use Triangular and Trapezoidal membership functions mostly?

The choice of the membership function clearly depends upon the problem we have chosen. There is no boundation on choosing a membership function. But for most of the problems triangular and trapezoidal membership functions are used because these two M.F gives the best result because of their simple formulas and as they can be easily computed. These two membership functions produce the optimum results.

3.4 FUZZY INFERENCE SYSTEM

Fuzzy inferencing method is basically an inferencing process for a given input so as to provide an output using knowledge base / rule base which consist of number of rules. This system helps the fuzzy controller to understand different parameters and to make the rules in accordance to it. The different blocks used in fuzzy inferencing are as follows:

i. Fuzzification
ii. Fuzzy Inference Engine
iii. Defuzzification

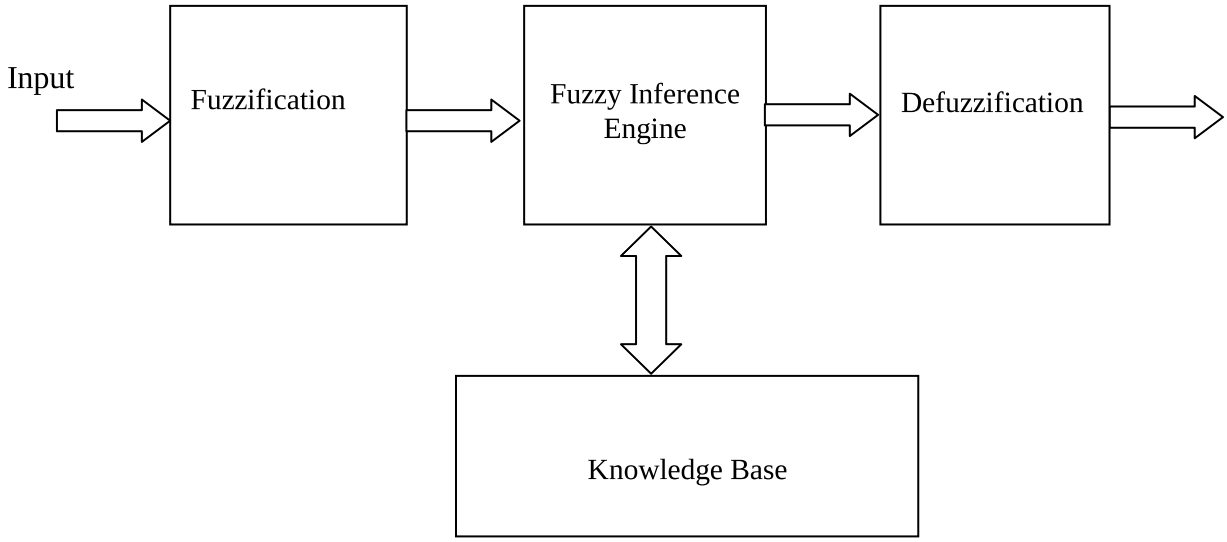


Fig 3.3 Fuzzy Inference System

3.4.1 FUZZIFICATION: It is a process of transforming a classical set into fuzzy set or it is a process of translating an uncertain event into fuzzy set by assigning a proper membership function or it is a process of transforming a scalar value into a fuzzy value. This is achieved with different types of fuzzifiers. There are generally three types of fuzzifiers, which are used for fuzzification process; they are Singleton fuzzifier, Gaussian fuzzifier and Trapezoidal or Triangular fuzzifier.

3.4.2 FUZZY INFERENCE ENGINE: These are the types of the method with the rule base so as to obtain the fuzzy values. There are basically two types of methods which we are using in this:

i. Mamdani method
ii. Sugeno method

Mamdani Method: It is a graphical technique of inference. It is a simple rule system which comprises of two hypotheses and one conclusion. This method is the most common, easy to understand and hence in use in most of the cases. Mamdani's logic gets its basics from the Lofti's Zadeh's 1973 paper. In this paper Lofti suggested fuzzy method or algorithm for decision making of complex systems. Mamdani using the method suggested by Lofti and using the linguistic control rules given by plant operators tried to control a steam engine and thus framed a rule base, now known as Mamdani's rule base.

Advantages of Mamdani Method:

a) It is intuitive.
b) It can be implemented in most of the problems.
c) It can easily be understood by humans as it contains language rules.

Sugeno Method: A type of fuzzy inference in which the consequent of each rule is a linear combination of the inputs. The output is a weighted linear combination of the consequents. It is suited to mathematical analysis.

Advantages of Sugeno Method:

a) It is computationally efficient.
b) It works well with linear techniques (e.g., PID control).
c) It has guaranteed continuity of the output surface.
d) It is well suited to mathematical analysis.

3.4.3 DEFUZZIFICATION: It is the reverse process of fuzzification. In defuzzification we convert the fuzzy set or fuzzy value into real set or real scalar. There are five methods for defuzzification:

i. Centroid method
ii. Bisector method
iii. Middle of Maximum
iv. Smallest of Maximum
v. Largest of Maximum

The most commonly used method among all is the centroid method.

- How to calculate centroid of a figure?

For symmetrical figure such as triangular, square, centroid lies at the centre. For complex objects the overall centroid is calculated by breaking it into smaller objects using a weighted average (by area).

$$C_x = \frac{\sum C_{ix} A_i}{\sum A_i}$$

C_i = Centroid of respective figure

A_i = Area of respective figure

3.5 ADVANTAGES OF FUZZY CONTROLLER OVER OTHER CONVENTIONAL CONTROLLERS

PID Controller exhibit good performance and accurate results mostly in case of linear systems but if there are non – linearity's in the system the performance reduces by a great extent. System containing oscillating signals dead zone and other non – linearity cannot be operated using PID controllers.

The number of parameters required for operation of PID is large. At least six parameters need to be estimated for PID controller operation which increases the complexity of the system. The parameters such as plant gain, time constant, time delay, proportional gain constant, integral gain constant, and derivative gain constant need to be calculated exactly.

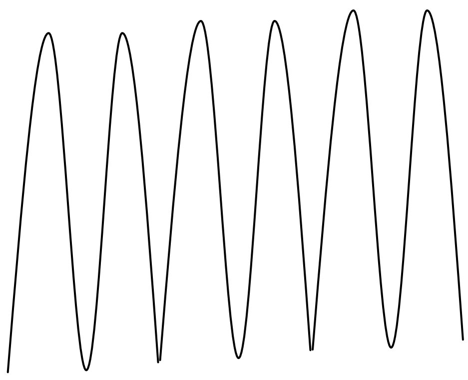
On the other hand Fuzzy Control is a suitable alternative in cases when the detailed structure of the system is not known and system follows some simple characteristics. The fuzzy logic is having the quality to capture the phenomenon involved in the system and then make suitable The capability of fuzzy logic to qualitatively capture the attributes of a control system and based on that making the desired rules makes it different from other controllers.. **Fuzzy logic is tolerant of imprecise data**: Most of the real life applications are imprecise and we cannot differentiate the processes easily. Fuzzy logic provides a platform to give a solution to these problems which looks to be very difficult to solve using simple methodologies. **Fuzzy logic is based on natural language:** As fuzzy logic consists of linguistic rules. So, it can be easily understood by human operators. Due to this only it can be easily communicated from one person to other. It gives one more advantage that we need not to learn any computer language or lengthy algorithms for its operation.

3.6 SUMMARY OF DISCUSSION OF FUZZY LOGIC

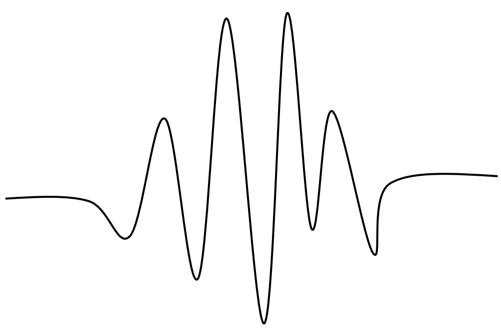
Fuzzy logic can be implemented for the differentiation of the inrush and the fault currents as fuzzy logic can be successfully applied to the non – linear quantities so we can use fuzzy logic for analysis and differentiation of inrush and fault currents. As fuzzy logic operates in parallel processing so with the increase in the number of inputs the computation time is not affected. With the increase in the number of inputs the complexity of the rule base increases.

3.7 FUNDAMENTALS OF WAVELET TRANSFORM

Wavelet transform is a methodology or transform to deal with the signals which cannot be processed using FFT transform and other available transforms. Its average value is zero and it is not like the other sinusoids which extends from minus to plus infinity. There range is limited. Wavelets are irregular in nature, they are also non – symmetrical and are very useful for the analysis of constant frequency signals. The signals containing unwanted oscillations and harmonics can also be operated by using wavelets. The below figure 3.4, shows the wavelet transform of a cosine wave at level 20.



Cosine Wave



Db 20 Wavelet

Figure 3.4: Wavelet Transform of Cosine wave

The other transforms such as FFT, DFT are useful tool for analysis of frequency components of signal but with these transforms we cannot comment on the time instants.

On the other hand wavelet transform focuses on high frequency components for short time interval and on low frequency components for long time interval. Due to this the analysis of the signals with localised impulses and oscillations increases manifolds.

3.8 NEED OF WAVELET TRANSFORM

In our analysis of the inrush and the fault currents what we have observed is that the inrushes current as well as the fault current signals are non – periodic in nature. It is also observed that these signals are oscillating in nature contains localised impulses superimposed on power frequency and its harmonics.

3.9 DISCRETE WAVELET TRANSFORM

Discrete Wavelet Transform is used to separate the data in various frequency components, as does the FFT. As FFT is used to separate unwanted signal such as noise from the original signal in the same sense DWT is also used for analysis of the signals and avoiding unwanted outages.

In FFT we cannot comment on specific time interval but in DWT we can remove the noise or frequency computed at some particular instant. This gives us a way to operate the signal in a different way as we can remove some unwanted signals at some particular interval as well as keep some useful data at some other point of interval. By using IDWT we can easily reconstruct the signal after removing the unwanted signals. Now through a block diagram we will see how DWT works:

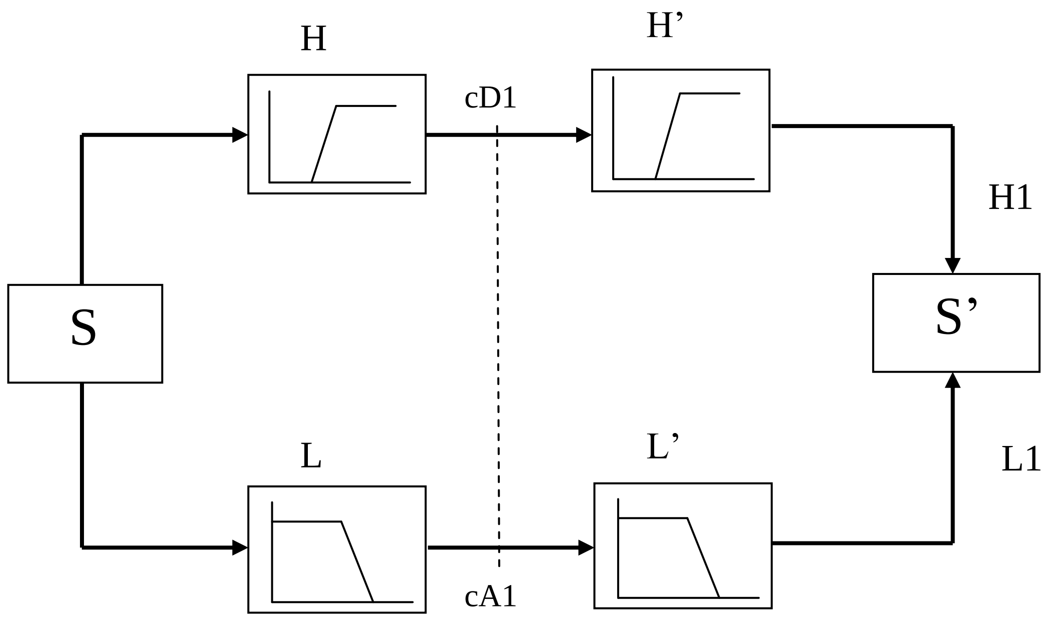


Figure 3.5: Single level Discrete Wavelet Transform

The discrete wavelet transform can be divided into two parts the left half which is known as decomposition and consists of the forward transform and the right half which consists of forward transform and is known as the reconstruction portion. In the middle is a line which is used to separate the two halves and is also used to add the complexity in the system. In figure 3.5 the input signal is passed through the high pass filter ‘H’ and coefficient cD1 is generated. This signal is further passed through a high pass reconstruction filter H’ to produce the detail coefficient H1. The signal S is also passed through a low pass decomposition filter L to produce the coefficient cA1, which is further passed through a low pass reconstruction filter L’ to produce the approximation L1. The upper filters H and H’ are the high pass filters and the lower filters L and L’ and the low pass filters.
Figure 3.5 showed a single level WT, while the below figure 3.6 shows a multi level WT.
In each step we down sampled the signal by 2 or we can say that decimation by 2.

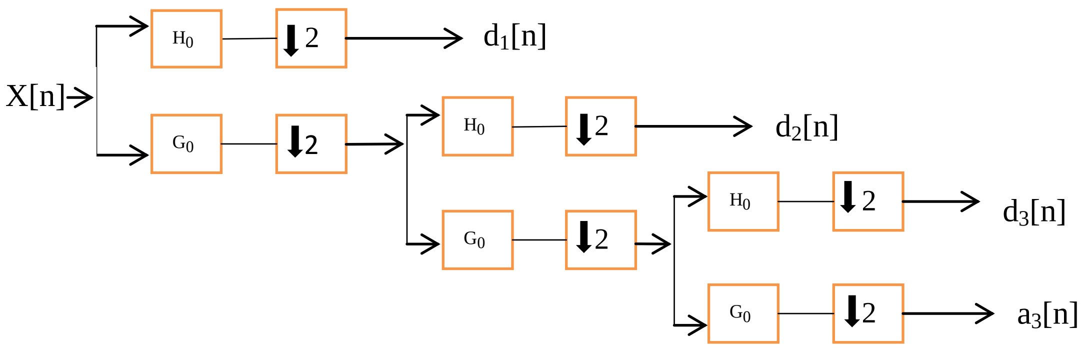


Figure 3.6: Implementation of Multi Level DWT

Where, H_o = High Pass Filter

G_o = Low Pass Filter

$d_1[n]$ = Level one decomposition

$d_2[n]$ = Level two decomposition and so on

$a_3[n]$ = Level three approximation

3.10 COMPARISION OF DWT WITH OTHERS

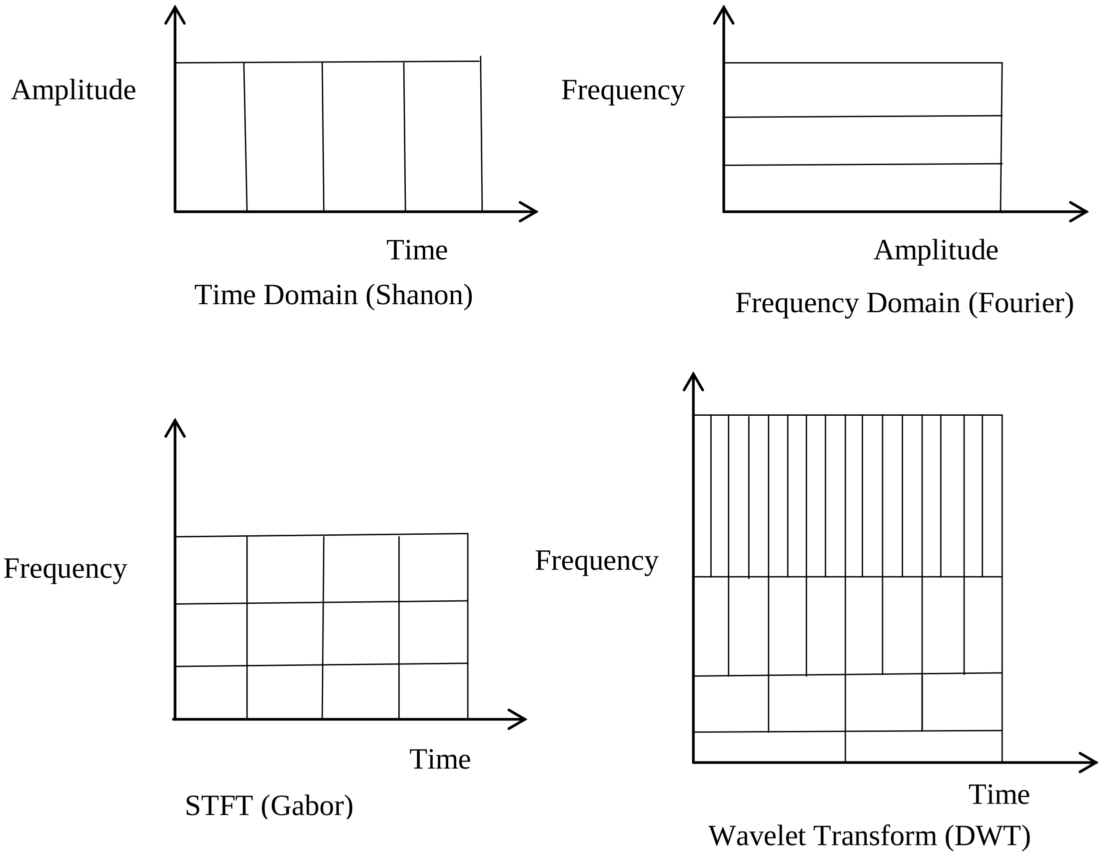


Figure 3.7: Different Transforms Methods

From here we can see that in case of DWT we can assign different time intervals for different frequency components. In the top block we have assigned a lower time interval and hence a higher frequency while in the bottom one we have assigned longer time interval and a low frequency.

3.11 SUMMARY OF DISCUSSION OF WT

After going through WT we can understand that two things play the major role in WT, one is the level of decomposition and the other is type of the transform. In my thesis I have used the Daubichies's (db – 6) wavelet and at level three. The max values of the level three (db – 6) I have extracted for further analysis.

CHAPTER 4

DISCRETE FOURIER TRANSFORM ANALYSIS

4.1 DFT ANALYSIS

DFT (Discrete Fourier Transform) is used to convert a signal from time domain to frequency domain as a signal can be easily analyzed in frequency domain. It converts each input sample to a particular frequency component and each sample is assigned a particular frequency. By converting the signal into frequency domain we will try to differentiate between the different phenomenons in our case. For this purpose we have taken one cycle (20ms) of the inrush current.

4.2 DFT ANALYSIS OF CURRENT SIGNALS FROM SILICON STEEL AND AMORPHOUS CORE

We have done the FFT analysis of inrush current obtained in the two cases (Amorphous alloy and Silicon Steel) and obtained the second harmonic content for the two.

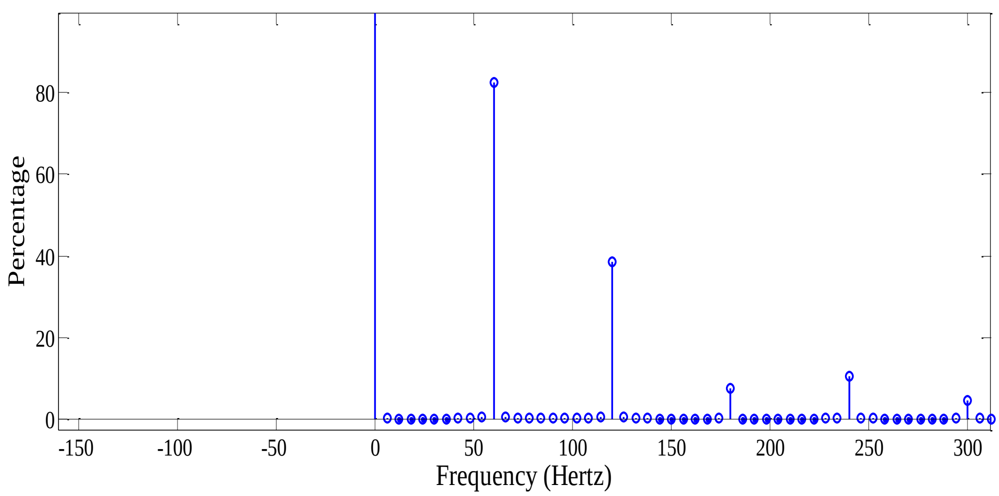


Figure 4.1: FFT Analysis of Inrush Current of Amorphous Core

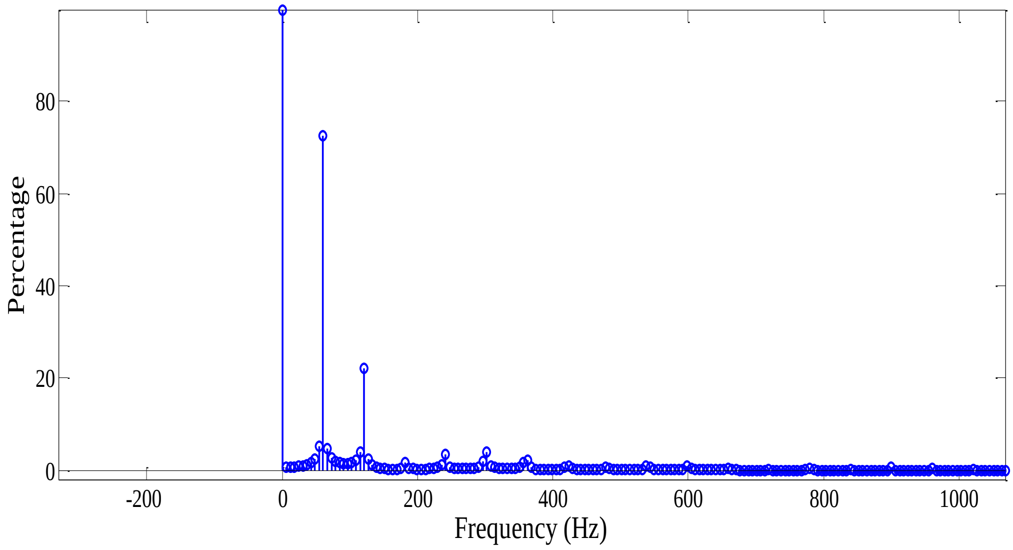


Figure 4.2: FFT Analysis of Inrush Current of Silicon Steel

Fundamental Frequency at 0 Hz

Second Harmonic is at 100 Hz

Second Harmonic Content for Amorphous Core: 36%

Second Harmonic Content for Silicon Steel: 23%

4.3 CONCLUSIONS: From the above analysis we conclude that second harmonic content is different for different core material. The percentage of second harmonic for amorphous alloy is greater than that for silicon steel. This is due to the fact of their different magnetizing properties.

4.4 ANALYSIS OF INRUSH CURRENT

Phase A (Second Harmonic Content = 36%)

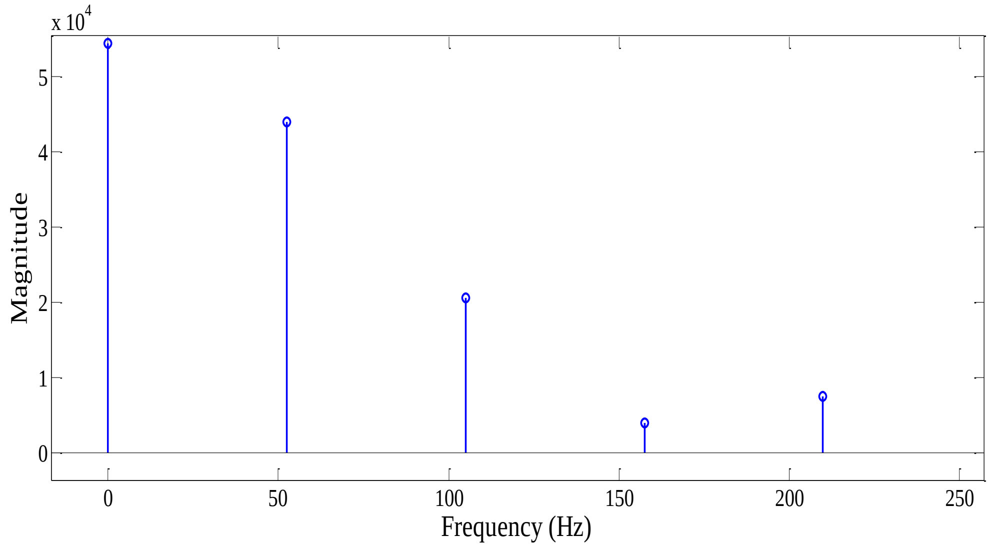


Figure 4.3: FFT analysis of phase A

Phase B (Second Harmonic Content = 73.5%)

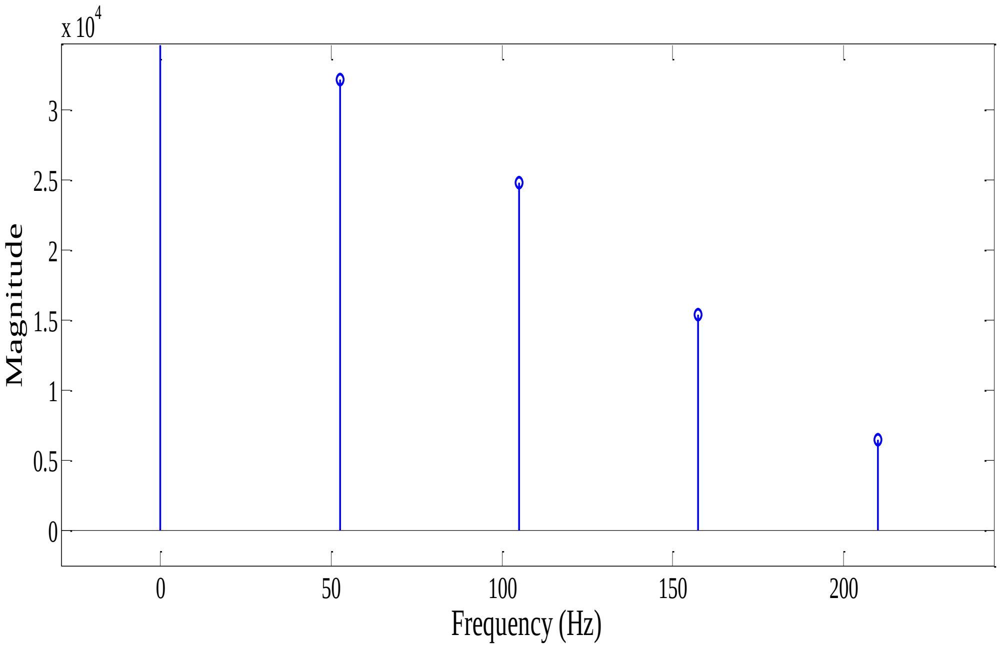


Figure 4.4: FFT analysis of Phase B

Phase C (Second Harmonic Content = 78.4%)

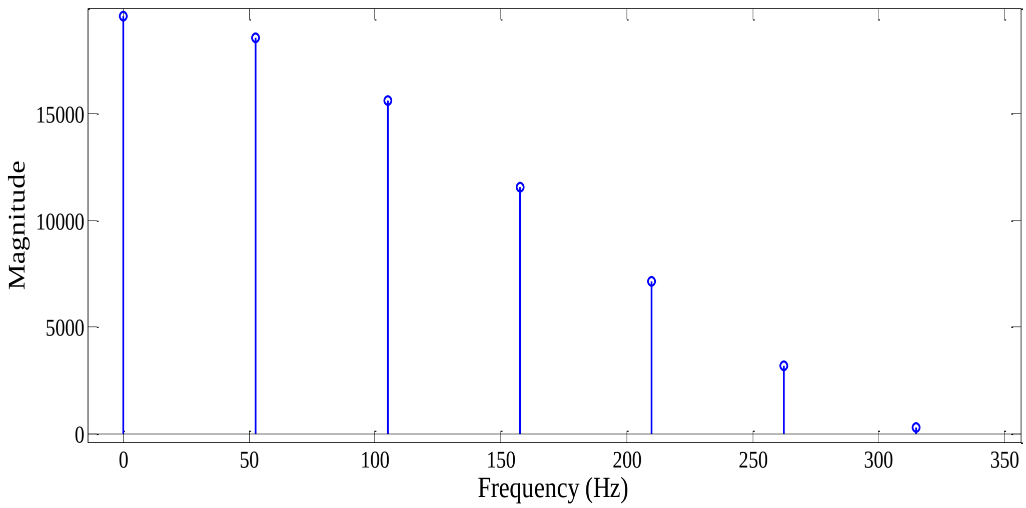


Figure 4.5: FFT analysis of phase C

4.5 ANALYSIS OF INTERNAL FAULT CURRENT

In the FFT analysis of the internal fault current first we have extracted one cycle from the original signal (internal fault signal). After extracting the signal, we have done its FFT analysis using the Matlab codes. The second harmonic content in each case is being observed and further analysis is being done. In figure 4.6 – 4.8 we have done single line to ground fault analysis. Figure 4.9 – 4.11 shows the two line to ground fault FFT analysis and figure 4.12 – 4.14 shows the three line to ground fault analysis.

4.5.1 L – G Phase A Fault (Second Harmonic Content = 65%)

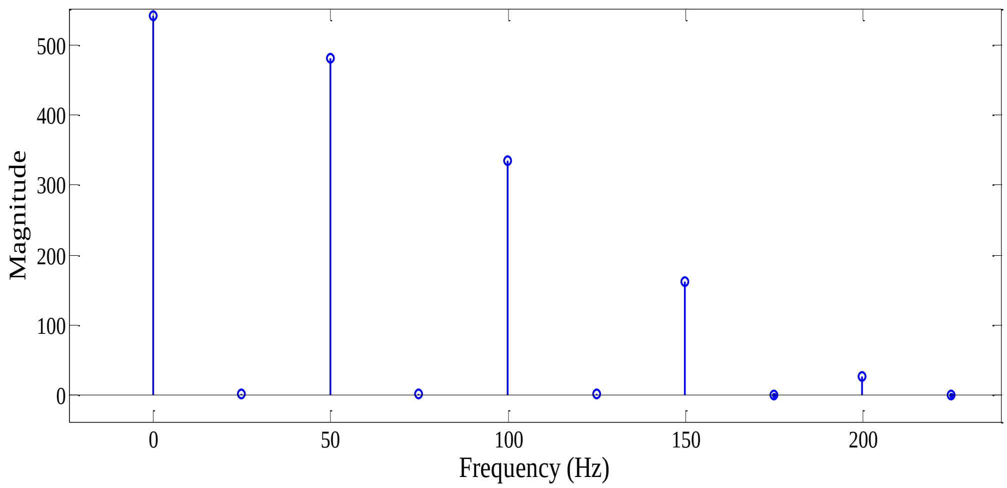


Figure 4.6: FFT analysis of L – G Phase A internal fault

4.5.2 L – G Phase B Fault (Second Harmonic Content = 24%)

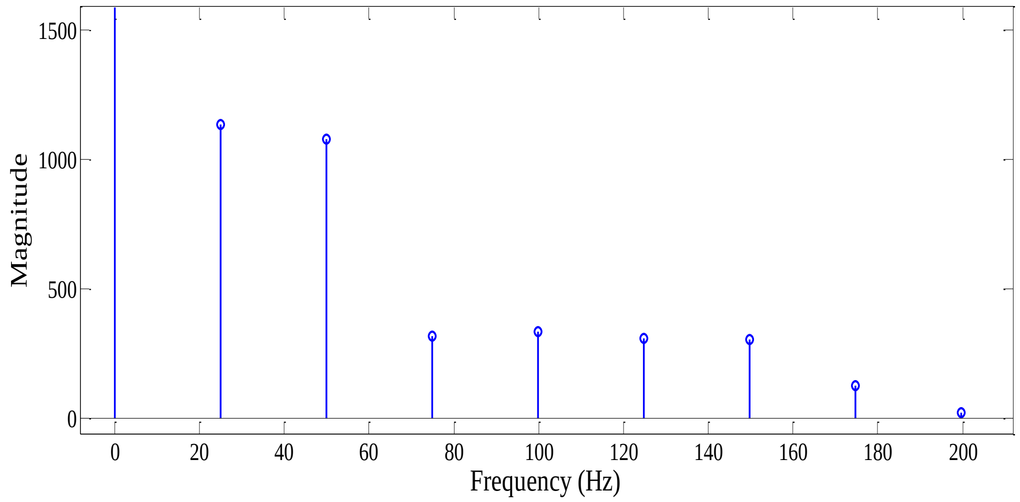


Figure 4.7: FFT analysis of L – G Phase B internal fault

4.5.3 L – G Phase C Fault (Second Harmonic Content = 25%)

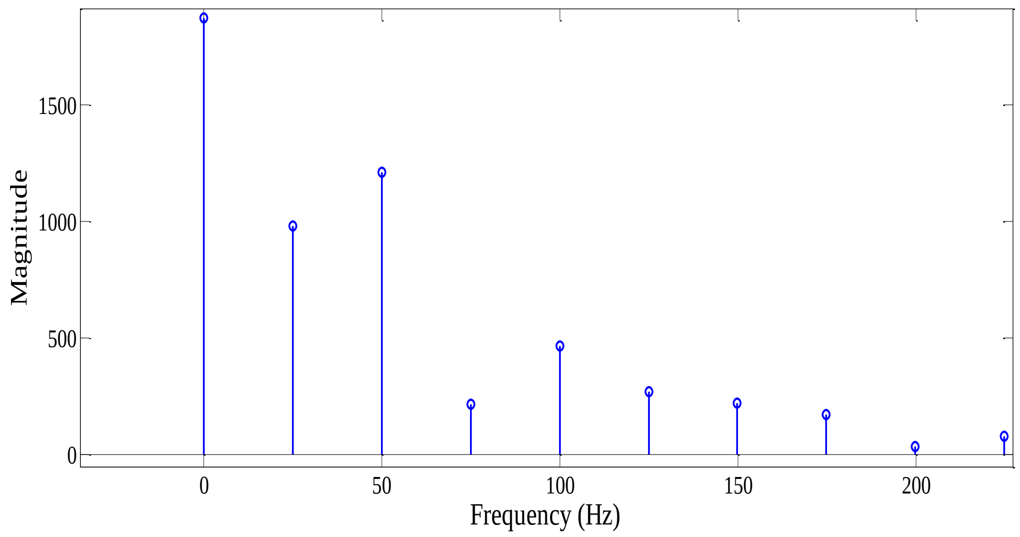


Figure 4.8: FFT analysis of L – G phase C internal fault

4.5.4 L – L – G Phase A Fault (Second Harmonic Content = 50%)

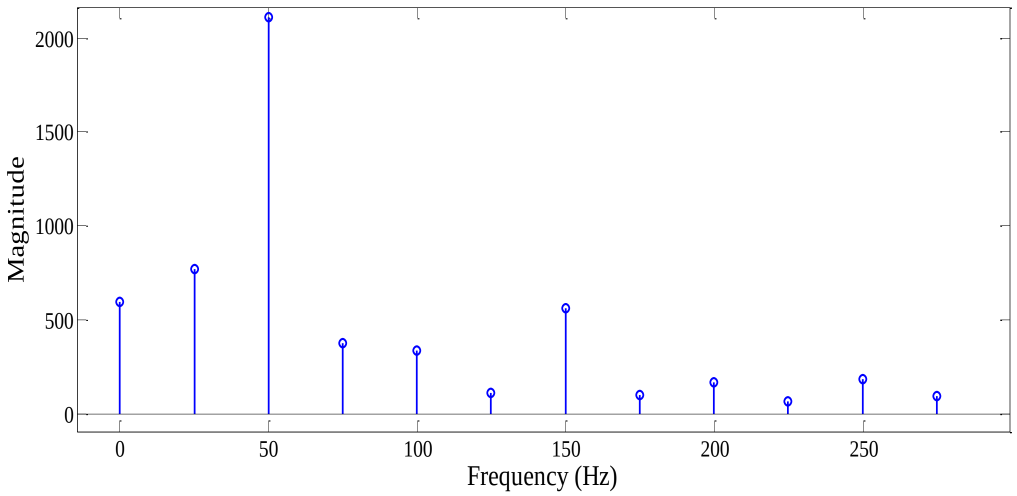


Figure 4.9: FFT analysis of L – L – G phase A internal fault

4.5.5 L – L – G Phase B Fault (Second Harmonic Content = 25%)

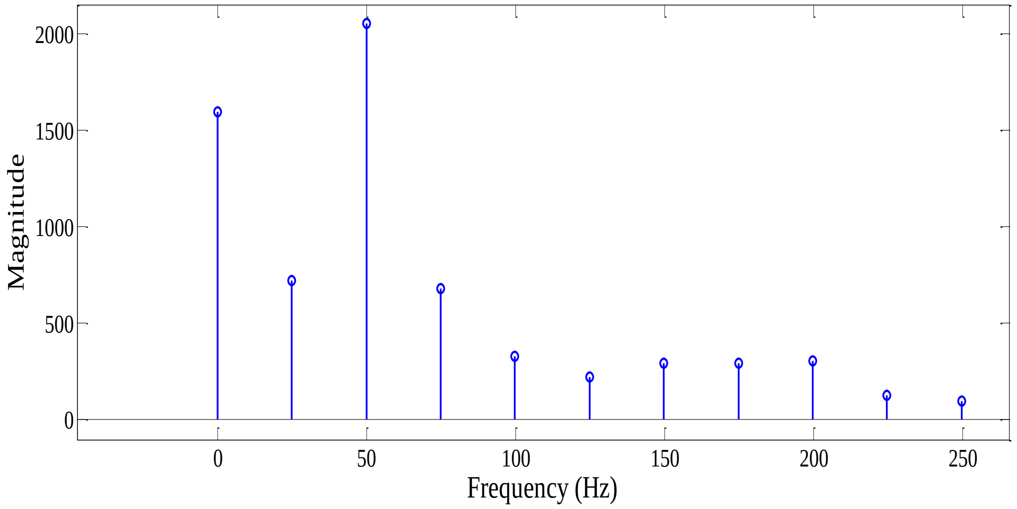


Figure 4.10: FFT analysis of L – L – G phase B internal fault

4.5.6 L – L – G Phase C Fault (Second Harmonic Content = 41%)

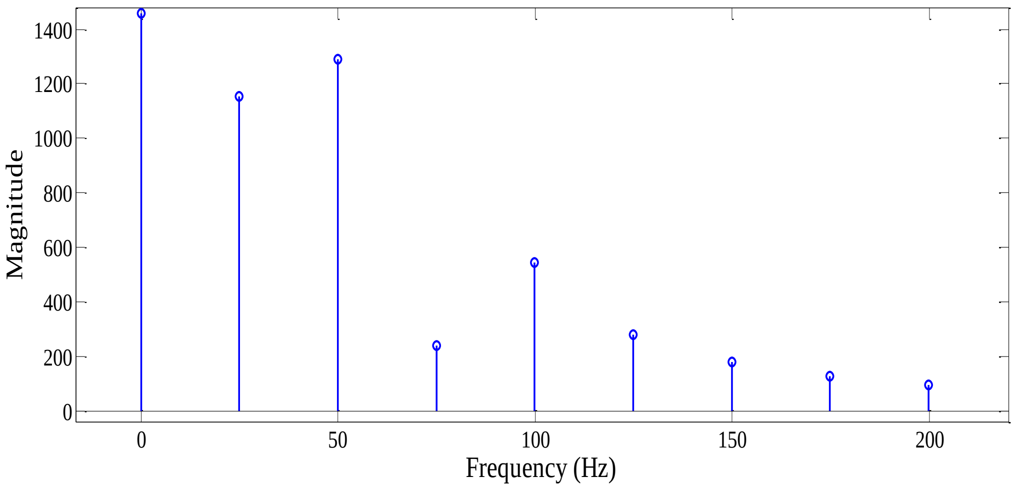


Figure 4.11: FFT analysis of L – L – G phase C internal fault

4.5.7 L – L – L – G Phase A Fault (Second Harmonic Content = 64.4%)

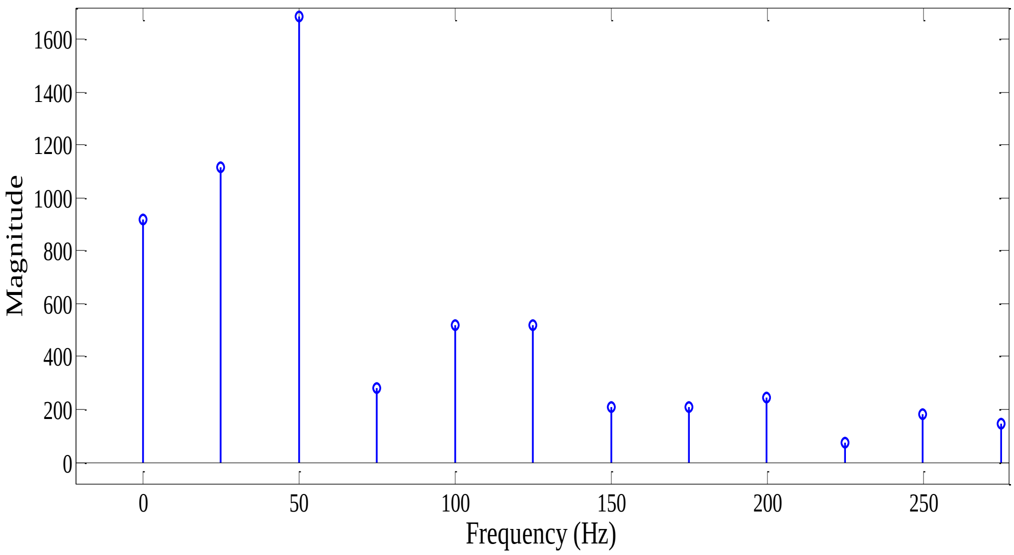


Figure 4.12: FFT analysis of L – L – L – G phase A internal fault

4.5.8 L – L – L – G Phase B fault (Second Harmonic Content = 50%)

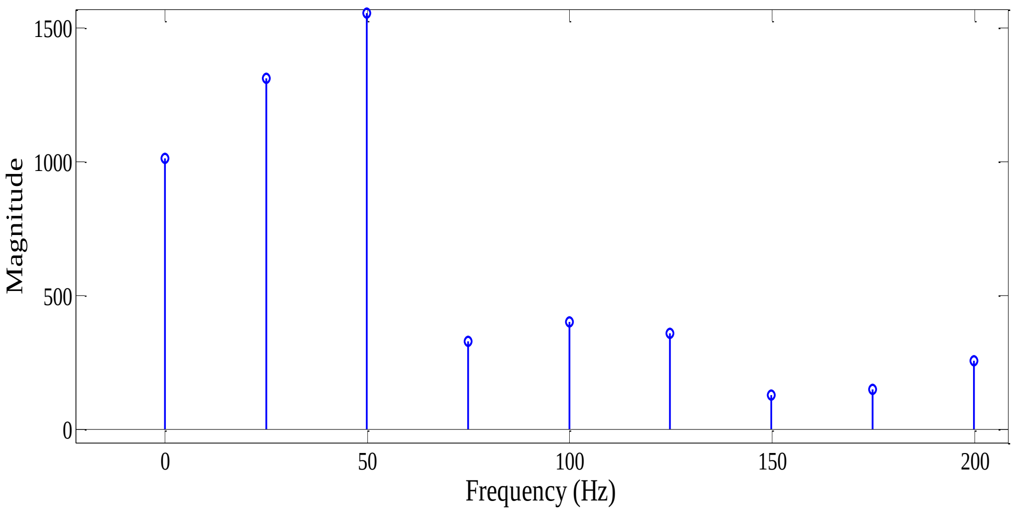


Figure 4.13: FFT analysis of L – L – L – G phase B internal fault

4.5.9 L – L – L – G Phase C Fault (Second Harmonic Content = 40%)

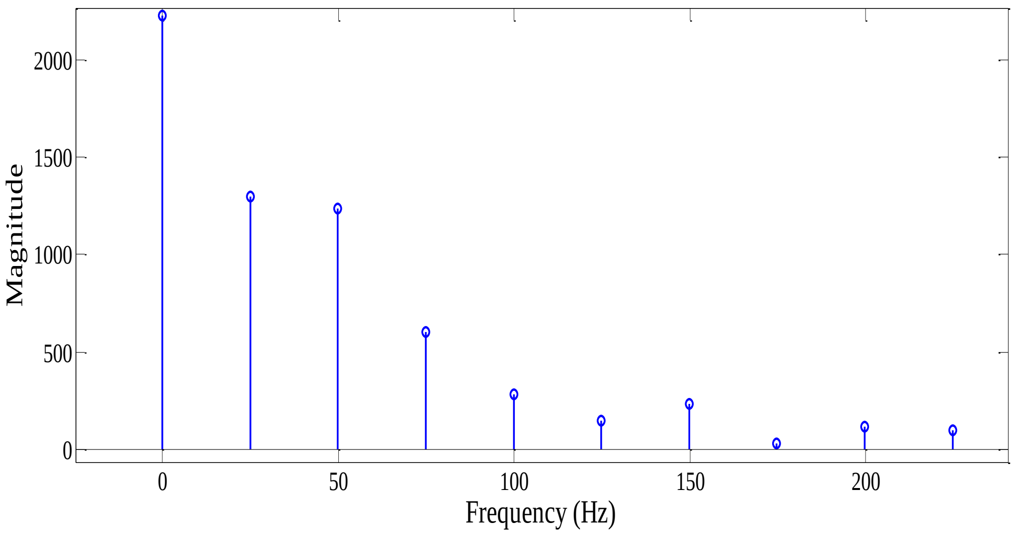


Figure 4.14: FFT analysis of L – L – L – G phase C internal fault

4.6 ANALYSIS OF EXTERNAL FAULT CURRENT

In the FFT analysis of external fault current we have extracted one cycle of the external fault current and the FFT analysis of that signal is being done. After taking the FFT we have noted down the second harmonic content in each case as we have done in the case of the internal fault. The below figure shows the FFT analysis of single, double and three line to ground external fault of Phase C.

4.6.1 L – G fault (Second Harmonic Content = 22.5%)

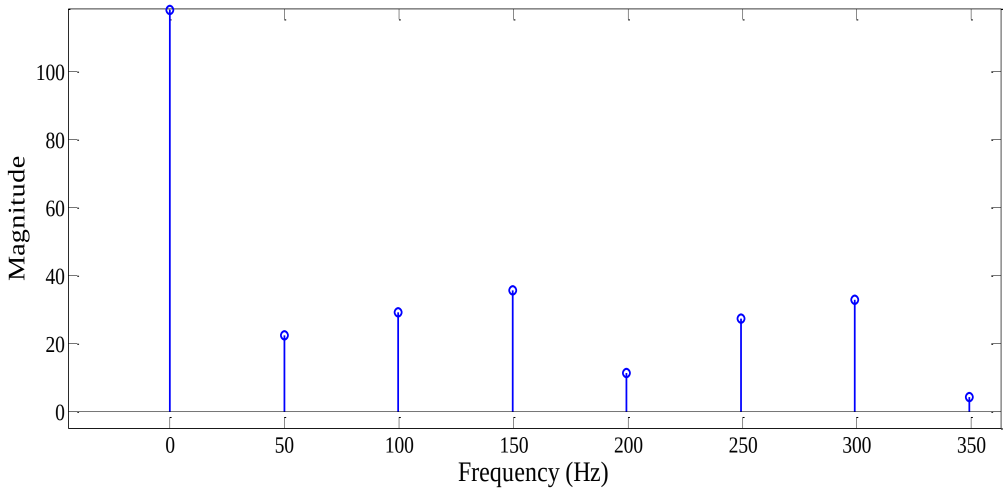


Figure 4.15: FFT analysis of L – G external fault

4.6.2 L – L – G fault (Second Harmonic Content = 21%)

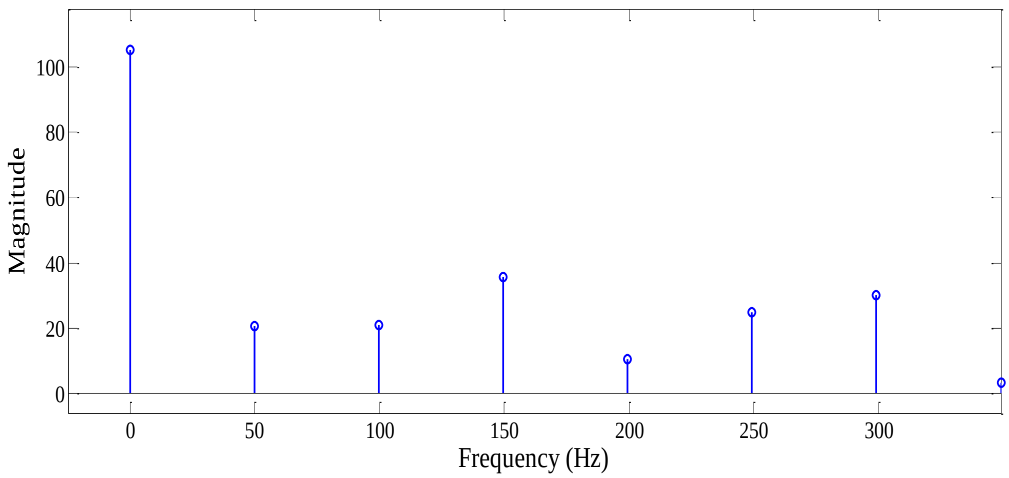


Figure 4.16: FFT analysis of L – L – G external fault

4.6.3 L – L – G fault (Second Harmonic Content = 24.8%)

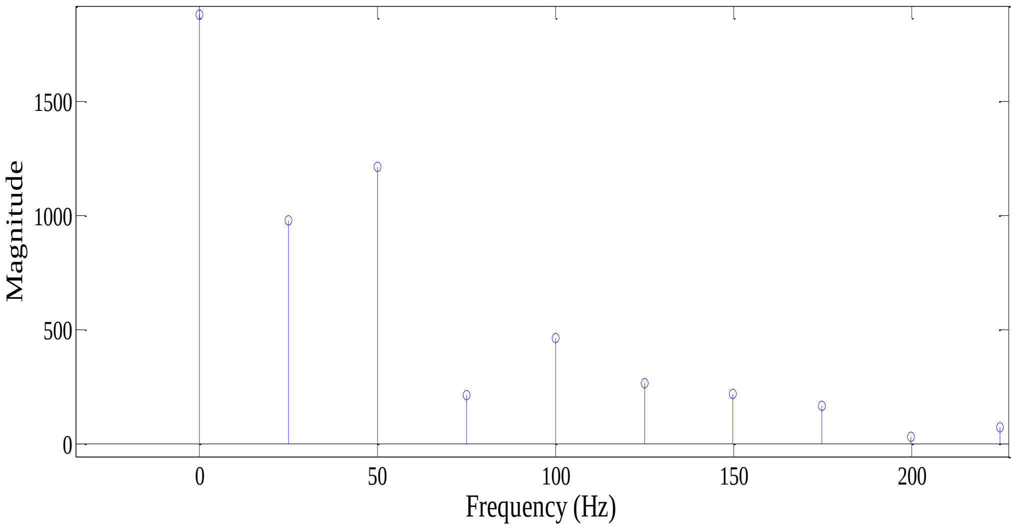


Figure 4.17: FFT analysis of L – L – G external fault

CHAPTER 5

DWT ANALYSIS

5.1 OVERVIEW

The Discrete Wavelet Transform is a transform technique in which we divide the full frequency band into two halves. The upper halve consists of the high pass filter and it gives the detailed analysis of the signal. Since the sampling frequency is 20 KHz, and according to Nyquist sampling theorem the sampling frequency should be twice the signal frequency. So in the first detailed analysis means in Detail – 1, we are having detailed coefficient of signals in the range 5 – 10 KHz. In detail – 2, we are having detailed coefficient of signals in the range 2.5 – 5 KHz and so on. The DWT technique used is db – 6 (Daubichies’s wavelet of level 6) as it best suits our case due to the oscillating and non – periodic nature of the inrush and internal fault current. The analysis is carried upto level 5 and different parameters are recorded at different levels for further analysis.

5.2 Inrush Current Original Signal

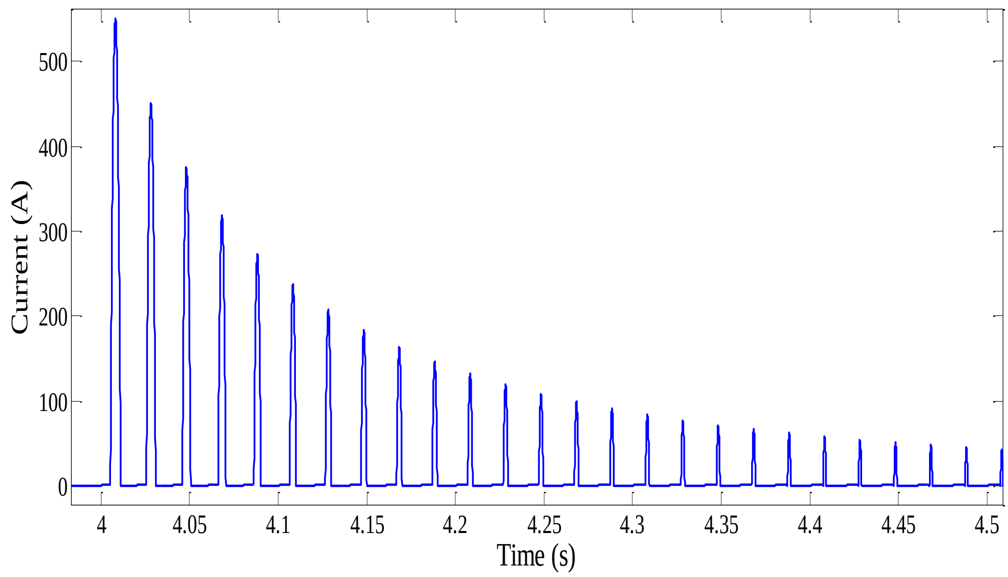


Figure 5.1: Inrush Current original signal

From the above obtained signal we have extracted the signal of the length of 20 ms and then we have taken its DWT up to level 5. The figures from 5.2 to 5.6 show the DWT analysis at different levels. It is seen that the magnitude of inrush current changed from nearly zero value to a significant value at the edges of the gaps. This sudden change from one state to other should produce small ripples. But these ripples are not visible in the time domain representation. These are clearly observed in the DWT. The changes in the amount of ripples can be seen with the increase in the level.

5.3 DWT ANALYSIS OF INRUSH CURRENT

5.3.1 Detail Coefficient at level 1 decomposition

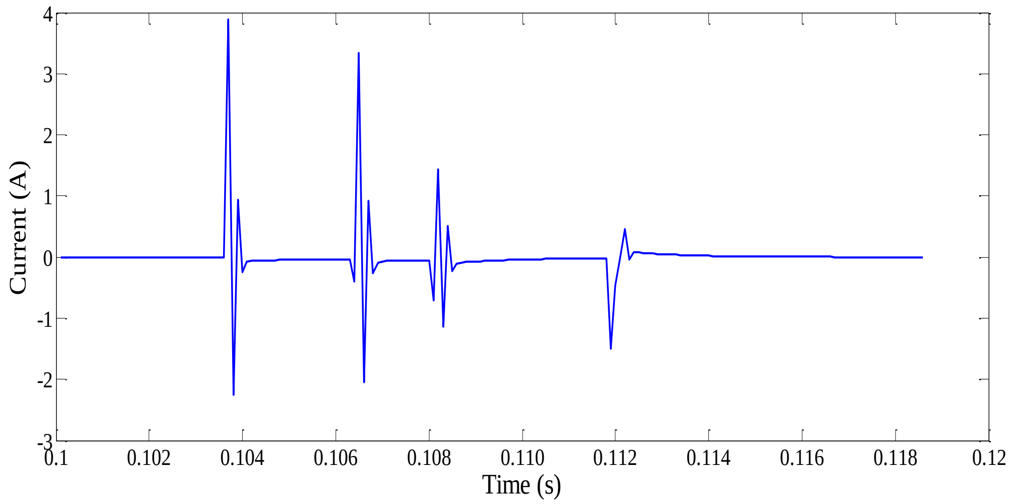


Figure 5.2: Wavelet analysis at level 1 decomposition

5.3.2 Detail Coefficient at level 2

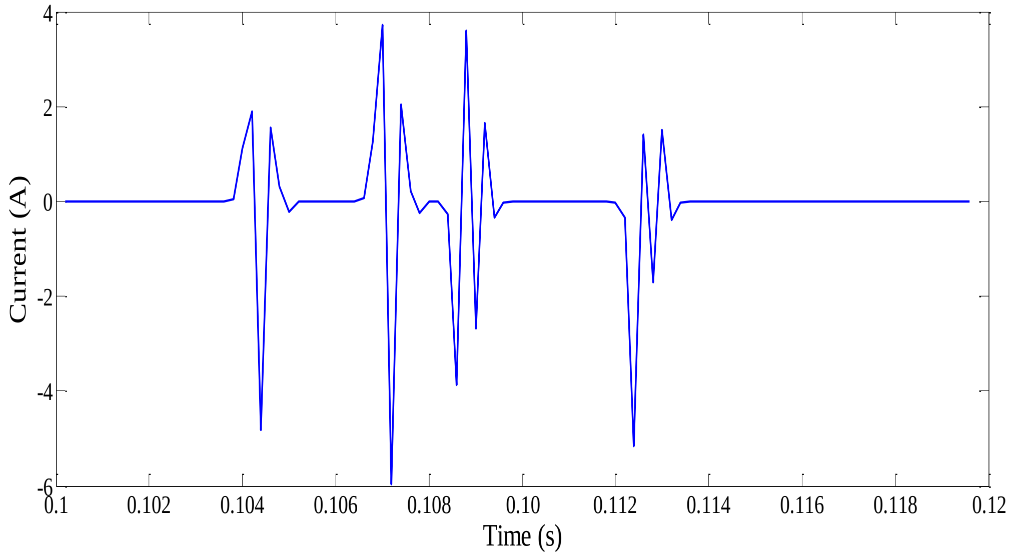


Figure 5.3: Wavelet analysis at level 2 decomposition

5.3.3 Detail Coefficient at level 3

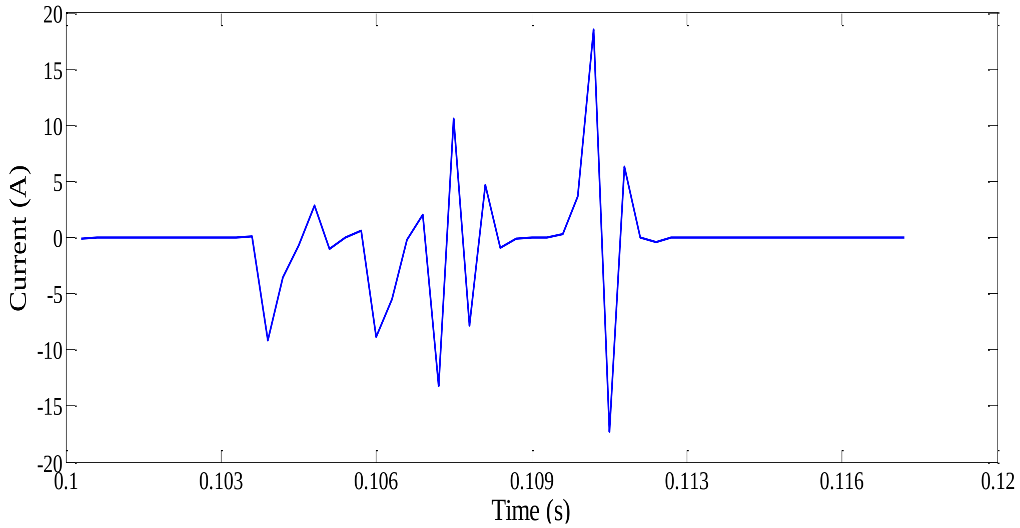


Figure 5.4: Wavelet analysis at level 3 decomposition

5.3.4 Detail Coefficient at level 4

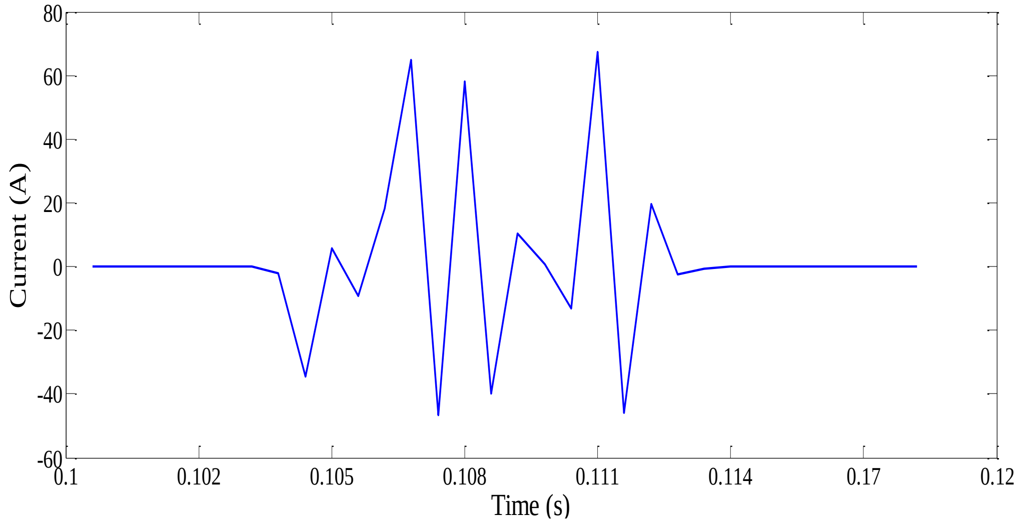


Figure 5.5: Wavelet analysis at level 4 decomposition

5.3.5 Detail Coefficient at level 5

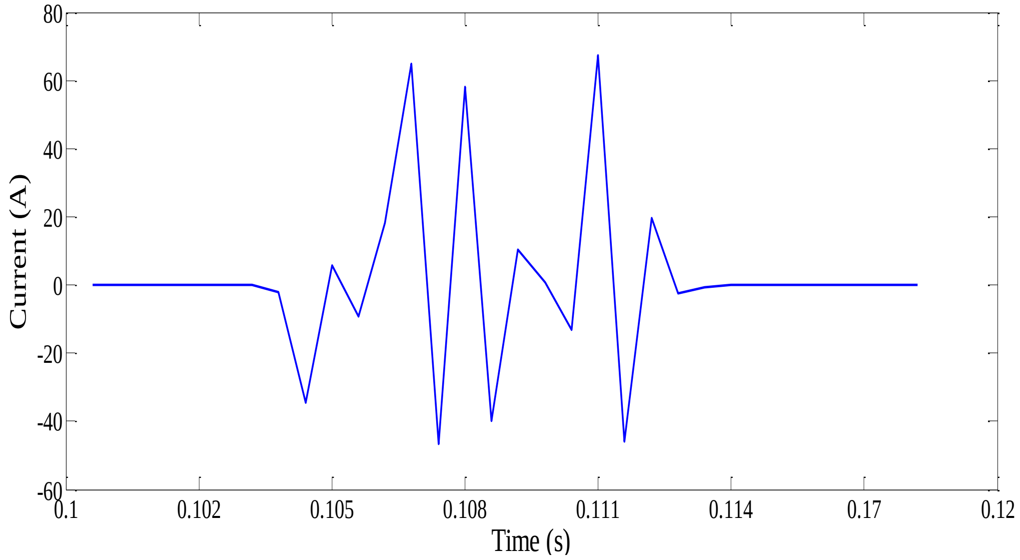


Figure 5.6: Wavelet analysis at level 5 decomposition

5.3.6 Frequency Band of different detailed coefficients

- Level 1 : 5 KHz – 2.5 KHz
- Level 2 : 2.5 KHz – 1.25 KHz
- Level 3 : 1.25 KHz – 0.625 KHz

- Level 4 : 0.625 KHz – 0.3125 KHz
- Level 5 : 0.3125 KHz – 0.15625 KHz

5.4 DWT ANALYSIS OF INTERNAL FAULT CURRENT

In the DWT analysis of internal fault current transient, first we have obtained the internal fault current in the figure 5.7 than from that we have extracted the one cycle of 20 ms and obtained the detailed coefficients in figures 5.8 – figure 5.12. The internal fault current is also oscillating in nature as well as non – periodic. The fault is of 12 Ω with the load being inductive in nature. In the DWT analysis of the internal fault what we have observed is that there are sharp spikes in the beginning but vanishes rapidly as we increases the level of DWT. On the other hand in case of inrush current these spikes could be observed over a longer period. Also from this we have obtained the different parameters such as maximum value, minimum value, mean etc. These parameters are further used in fuzzy logic controller to differentiate the transients.

5.4.1 Internal Fault Current

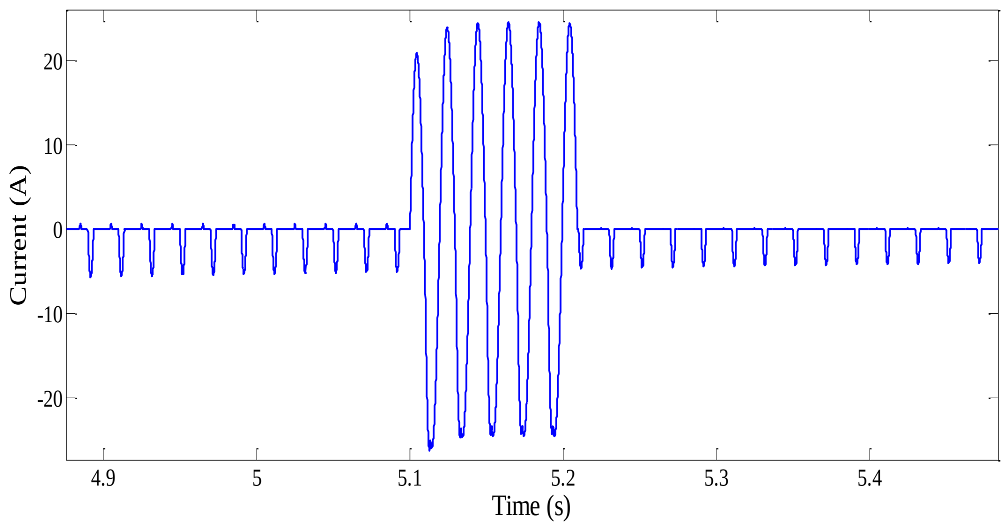


Figure 5.7: Internal fault current original signal

5.4.2 Detail Coefficient at level 1 Decomposition

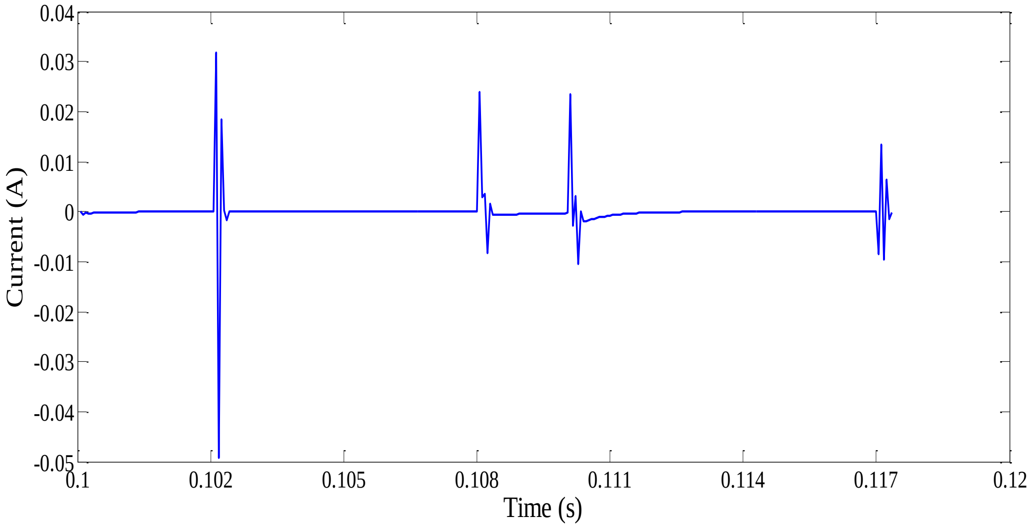


Figure 5.8: Wavelet analysis at level 1 decomposition

5.4.3 Detail Coefficient at level 2

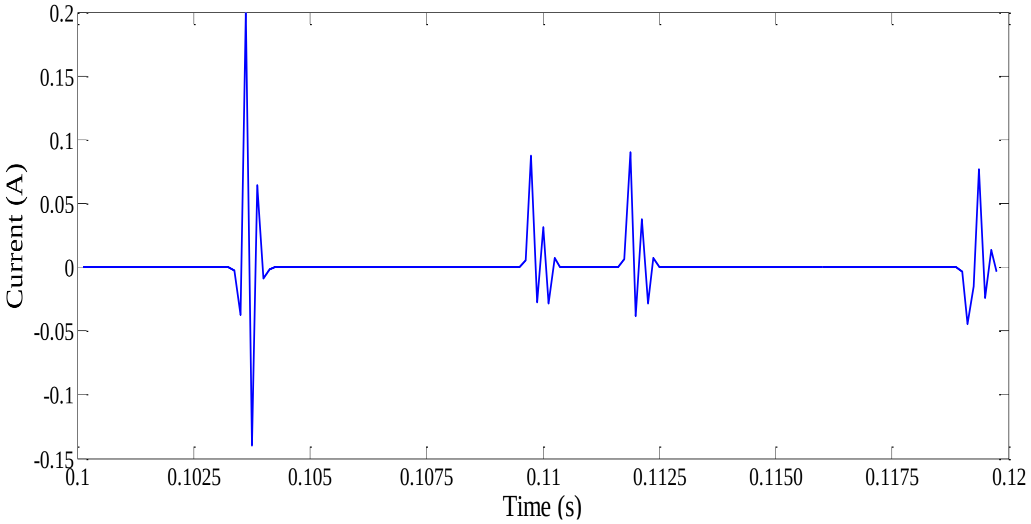


Figure 5.9: Wavelet analysis at level 2 decomposition

5.4.4 Detail Coefficient at level 3

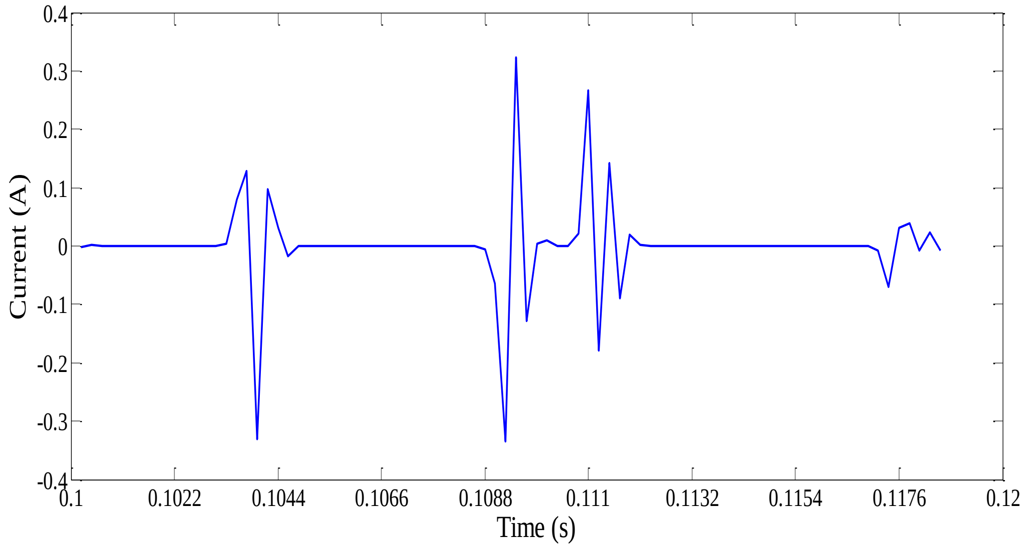


Figure 5.10: Wavelet analysis at level 3 decomposition

5.4.5 Detail Coefficient at level 4

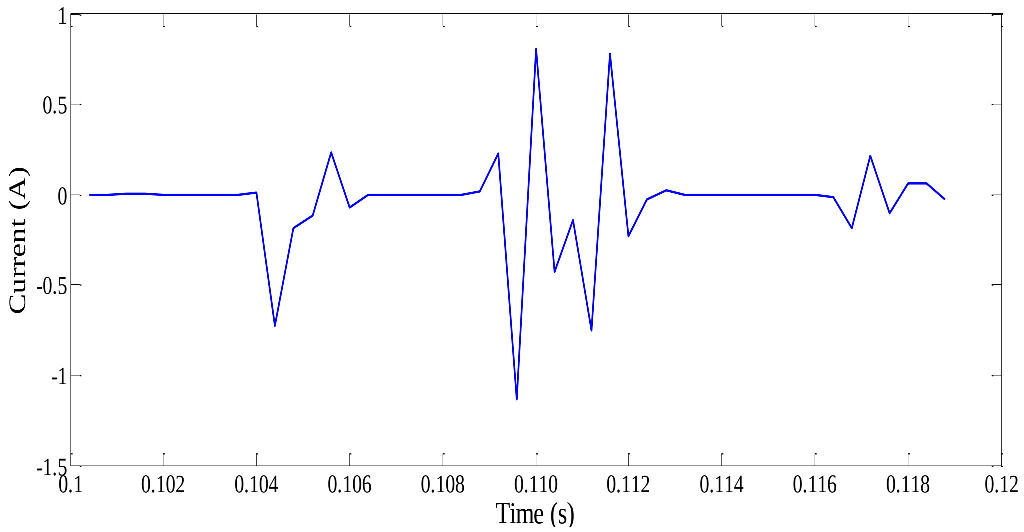


Figure 5.11: Wavelet analysis at level 4 decomposition

5.4.6 Detail Coefficient at level 5

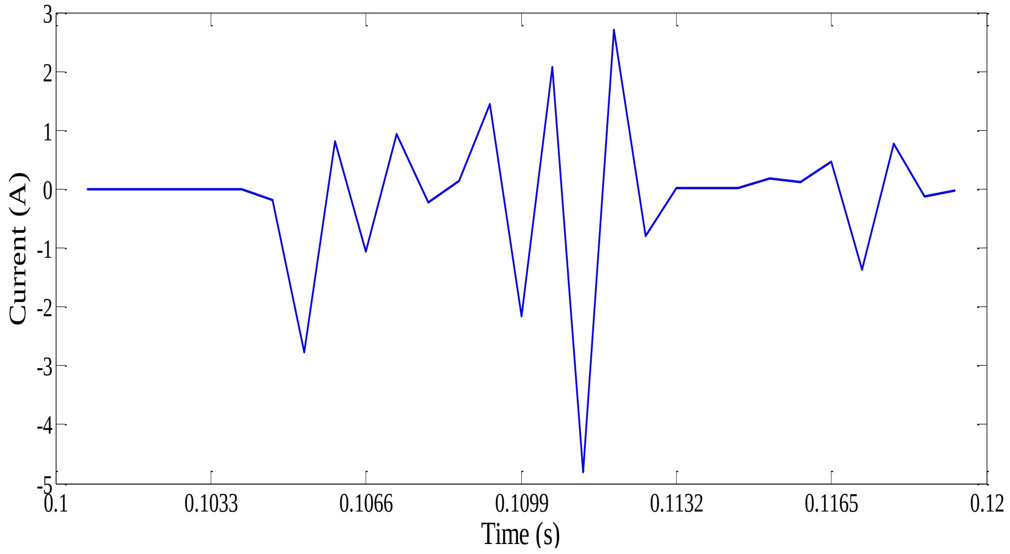


Figure 5.12: Wavelet analysis at level 5 decomposition

CHAPTER 6

IMPLEMENTATION WITH FUZZY LOGIC

6.1 OVERVIEW

In this chapter we have discussed how to implement fuzzy logic controller for differentiating power transformer transients. For the implementation with fuzzy logic there should be some parameter using which we can differentiate or can make rules for their separation. For this purpose, earlier we have done the DWT analysis of the different transients. From there we have extracted the maximum value of different parameters at different levels. After that we have framed the rules using Mamdani model of rule base.

6.2 INRUSH CURRENT ANALYSIS

Table 6.1: Max value after DWT analysis of Inrush current

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
15^0	3.1969	7.3749	7.9691
30^0	3.8877	3.7111	18.5682
45^0	2.6312	8.6265	18.7881
60^0	2.77	8.23	8.71
75^0	0.6905	8.5321	20.9283
90^0	3.2744	7.9243	20.5690
105^0	1.2763	4.2402	11.6787
120^0	2.0849	3.8623	18.4850

In the DWT analysis of the inrush current, the maximum values at different levels are obtained. It is found that the max value among all the levels is observed in level 3 and minimum is observed in level 1. At different levels of switching, different values are obtained. From here we have made a range for the inrush current. We have used the values in fuzzy controller after multiplying by 100. It is done for ease of computation.

6.3 INTERNAL FAULT CURRENT ANALYSIS

For 3 line to ground fault

Table 6.2: Max value after DWT analysis of 3 line to ground fault

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
0^0	0.0576	0.2964	0.3946
30^0	0.0576	0.2970	0.3942
60^0	0.0576	0.2971	0.3946
90^0	0.0580	0.2967	0.3944
120^0	0.0576	0.2964	0.3946

For 2 line to ground fault

Table 6.3: Max value after DWT analysis of 2 line to ground fault

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
0^0	0.0318	0.1997	0.3234
30^0	0.0313	0.1999	0.2704
60^0	0.0313	0.1999	0.2700
90^0	0.0307	0.2001	0.3273
120^0	0.0309	0.1996	0.2700

For 1 line to ground fault

Table 6.4: Max value after DWT analysis of 1 line to ground fault

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
0^0	0.0299	0.0960	0.3235
30^0	0.0277	0.078	0.2705
60^0	0.0312	0.0695	0.2700
90^0	0.0270	0.0935	0.3274
120^0	0.0285	0.0937	0.3210

In the DWT analysis if the internal fault current it is observed that the maximum values at different level of computation is less as compared to the inrush case. Also, it is observed that the values keep on increasing with the level of computation as in the case of inrush. But the values remain almost constant at different angles of switching in one particular type of fault. As we have multiplied the inrush values by a factor of 100, so here also we multiply every value by the same factor. After that we have noted the range of the values from the maximum to minimum for this case to frame the input and the rules.

6.4 EXTERNAL FAULT CURRENT ANALYSIS

For 3 line to ground fault

Table 6.5: Max value after DWT analysis of 3 line to ground fault

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
0^0	0.0011	0.0065	0.0089
30^0	0.0012	0.0065	0.0089
60^0	0.0011	0.0065	0.0089
90^0	0.0014	0.0061	0.0085
120^0	0.0012	0.0064	0.0088

For 2 line to ground fault

Table 6.6: Max value after DWT analysis of 2 line to ground fault

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
0^0	0.0011	0.0064	0.0087
30^0	0.0011	0.0065	0.0089
60^0	0.0019	0.0065	0.0089
90^0	0.0016	0.0064	0.0085
120^0	0.0012	0.0064	0.0089

For 1 line to ground fault

Table 6.7: Max value after DWT analysis of 1 line to ground fault

Switching Angle	Maximum Value		
Degree	Level 1	Level 2	Level 3
0^0	0.0042	0.0607	0.1493
30^0	0.0008	0.0054	0.093
60^0	0.026	0.0473	0.0853
90^0	0.0005	0.0455	0.0853
120^0	0.0260	0.0473	0.1183

In the DWT analysis of the external fault current it is observed that the maximum values of the transients are smallest compared to the other two. It is observed that the values are increasing with the increase in the level of computation as in the other two cases. The values remain almost constant for the 3 line to ground fault and the 2 line to ground fault. Some changes are observed in the case of 1 line to ground fault with the change in the switching angle. The values obtained in the case of external fault current are quite less compared to inrush and the internal fault case. Hence can be easily differentiated. As the values observed in this case are very small therefore for ease of computation we have multiplied all the values by a factor of 100. Due to this only we have to multiply the values by 100 in the other to cases. On the basis of the values which we have obtained, the range for the external fault is being selected.

6.5 FUZZY CONTROLLER

In the fuzzy controller there are three blocks input, output and the rule base. Based on the values obtained by the DWT transform we have made three different inputs at the three different levels. The first input is the Level – 1 detailed coefficient ranging from 0 to 500. The second input is the Level – 2 detailed coefficient with the range from 0 to 1200. The third input is the Level – 3 detailed coefficient with the range from 0 to 2500. In the output block we have only one single output with three different parameters external fault with range from 0 to 30, internal fault with range from 30 to 60 and inrush with range from 60 to 90. The third block in the fuzzy controller is the rule base in which we have framed different rules.

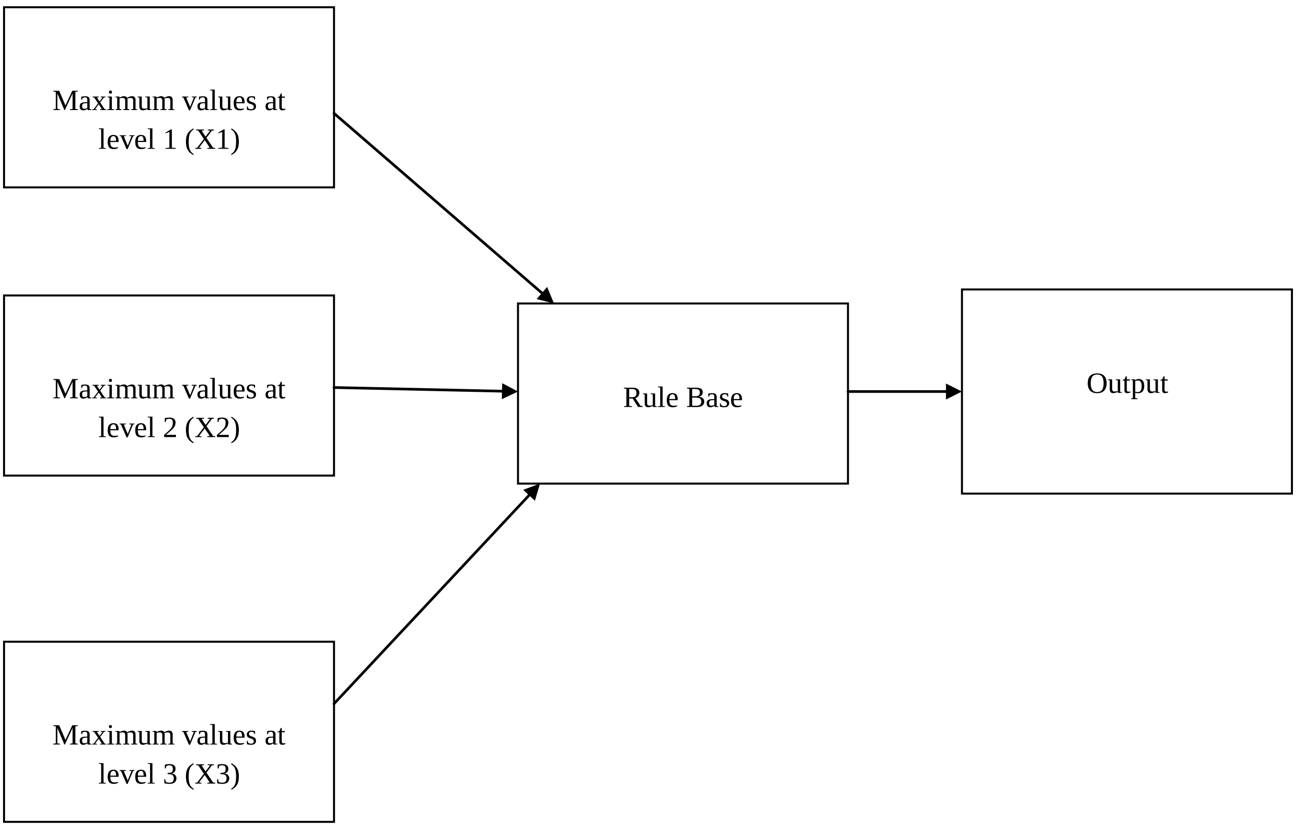


Figure 6.1: Block Diagram of Fuzzy controller

Input Parameters

Table 6.8: Parameters at level 1 (X1)

Name	Type	Range
Low	Trapezoidal	[-1 0 1 2]
Medium	Triangular	[0 25 50]
High	Trapezoidal	[40 250 350 500]

Table 6.9: Parameters at level 2 (X2)

Name	Type	Range
Low	Trapezoidal	[-1 1 2 5]
Medium	Triangular	[0 50 100]
High	Trapezoidal	[80 600 850 1200]

Table 6.10: Parameters at level 3 (X3)

Name	Type	Range
Low	Trapezoidal	[-1 5 10 20]
Medium	Triangular	[0 50 100]
High	Trapezoidal	[80 1200 1900 2500]

Output Parameters

Table 6.11: Output parameters

Name	Type	Range
External	Triangular	[0 15 30]
Internal	Triangular	[30 45 60]
Inrush	Triangular	[60 75 90]

Rule Base

1. If (X1 is low) and (X2 is low) and (X3 is low) then (output is external).
2. If (X1 is low) or (X2 is low) or (X3 is low) then (output is external).
3. If (X1 is medium) and (X2 is medium) and (X3 is medium) then (output is internal).
4. If (X1 is medium) or (X2 is medium) or (X3 is medium) then (output is internal).
5. If (X1 is high) and (X2 is high) and (X3 is high) then (output is inrush).
6. If (X1 is high) or (X2 is high) or (X3 is high) then (output is inrush).

CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7.1 CONCLUSIONS

FFT Analysis

From the FFT analysis we concluded that the magnitude of inrush current is different for different cores. We have found in our analysis that inrush current is higher for amorphous core as compared to the CRGO steel. This is due to the fact of their different magnetization properties.

In the FFT analysis of inrush, internal and external fault, we have observed that the second harmonic content of the inrush current is lying in the high range almost above 50%. The second harmonic content for external fault in all the cases is lying below 25%. So, we can easily differentiate the inrush and external fault transients on the basis of FFT analysis. But in the FFT of internal fault the second harmonic content varies from 25% to upto 70%. So, we conclude that we can differentiate the external fault from inrush on the basis of FFT analysis but we cannot differentiate internal fault transients from inrush and external fault transients on this basis. This is due to the fact that in the FFT analysis signals are analyzed only in the frequency domain, we cannot comment on the instant of time at which the transients are occurring. So, we need to look for some other transforms like Clarke's transform, Wavelet transform. Wavelet transform could be a useful tool for our analysis as it focuses both in frequency and time domain.

DWT Analysis

In the DWT analysis we have analysed both the inrush and internal fault currents using daubichies wavelet transform (dB – 6) up to level 5. In the DWT analysis of the internal fault what we have observed is that there are sharp spikes in the beginning but vanishes rapidly as we increases the level of DWT. On the other hand in case of inrush current these spikes could be observed over a longer period. In DWT analysis we have also calculated the max value for each case at different levels.

We have observed that the max value at each level of computation is found to be maximum in case of inrush and minimum in case of external fault. The value in case of internal fault lies in between the inrush and external fault.

Fuzzy Analysis

Fuzzy logic controller have been successfully implemented for the differentiation of Inrush, Internal and External fault (Power Transformer Transients) using the detailed coefficients obtained by wavelet analysis. We have manually given the data obtained in wavelet transform to the input of the fuzzy controller. Fuzzy logic controller being intelligent controller is found to be a very useful tool for classification of faults.

7.2 FUTURE SCOPE OF THE PROJECT

- Make an experimental setup for the same.
- Try to simulate the same using increased membership function and different rules so as to obtain better results.
- Use some other wavelet transforms for the same to obtain improved results and increased efficiency.

APPENDIX – I

Parameters of Power System

Source

Three phase 735 KV, 50 Hz

Source Resistance = 0.001 Ω

Source Inductance = 0.2 mH

Transformer

250 MVA, 50 Hz, delta – star connected

HV winding

Voltage = 315 KV, Resistance = 0.02 pu, Inductance = 0.08 pu

LV winding

Voltage = 735 KV, Resistance = 0.02 pu, Inductance = 0.08 pu

Primary CT Ratio

200/5

Secondary CT Ratio

800/5

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